To Kit or Not to Kit:
optimalisatie van de interne lijnbevoorrading
in de auto-assemblage-industrie

To Kit or Not to Kit:
Optimizing Part Feeding in the Automotive Assembly Industry

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Picture a martial artist kneeling before the master sensei in a ceremony to receive a hard-earned black belt. After years of relentless training, the student has finally reached a pinnacle of achievement in the discipline.

"Before granting the belt, you must pass one more test," says the sensei.
"I am ready," responds the student, expecting perhaps one final round of sparring.
"You must answer the essential question: What is the true meaning of the black belt?"
"The end of my journey," says the student. "A well-deserved reward for all my hard work."
The sensei waits for more. Clearly, he is not satisfied. Finally, the sensei speaks. "You are not yet ready for the black belt. Return in one year."
A year later, the student kneels again in front of the sensei.
"What is the true meaning of the black belt?" asks the sensei.
"A symbol of distinction and the highest achievement in our art," says the student.
The sensei says nothing for many minutes, waiting. Clearly, he is not satisfied. Finally, he speaks. "You are still not ready for the black belt. Return in one year."
A year later, the student kneels once again in front of the sensei. And again the sensei asks: "What is the true meaning of the black belt?"
"The black belt represents the beginning – the start of a never-ending journey of discipline, work, and the pursuit of an ever-higher standard," says the student.
"Yes. You are now ready to receive the black belt and begin your work."

(Collins, J. & Porras, J., 1996:199-200)

Acknowledgments

Being a graduate student is like becoming all of the Seven Dwarves. In the beginning you're Dopey and Bashful. In the middle, you are usually sick (Sneezy), tired (Sleepy), and irritable (Grumpy). But at the end, they call you Doc, and then you're Happy.

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Gent, 22 december 2011
Veronique Limère

Notation

Sets

I_b	Set of all parts supplied in small boxes
I_p	Set of all palletized parts
I	Set of all parts; $I = I_p \cap I_b$
I_s	Set of all parts used at station s
S	Set of all work stations s
V_i	Set of variant parts of $i \in I$; the family of part i

Parameters

a_i	Maximum number of units of a part i in one pick due to physical characteristics (weight, volume) of part i	
A^b	Capacity of the milk run tours for boxes (number of boxes per tour)	
A^k	Capacity of the milk run tours for kits (number of kits per tour)	
B^k	Batch size for assembling kits	
Δ_{is}^{bulk}	Average distance for the operator at workstation s to pick from a bulk container of part i	(m)
Δ_{is}^{k}	Average distance for the operator in the supermarket to pick from a bulk container of part i to kit for station s	(m)

Δ^k	Average distance for the line-operator to pick from a kit	(m)
d	Yearly demand for end product (= vehicle)	
D^b	Distance of the milk run tour for boxes	(m)
D^k	Distance of the milk run tour for kits	(m)
D_s^p	Distance of transport between the pallet warehouse and work station s	(m)
$depth$	The depth of the line - i.e. the perpendicular distance between the operator working at the product and the border of line	(m)
f_{is}	Percentage of end products for which part i is assembled at station s (frequency)	
FT^k	Fixed production time for each kit	(h)
H^b	Vertical stacking height of boxes (units) on the BoL	
L^b	Length of a box along the line	(m)
L^k	Length of a kit container/rack along the line (we assume no stacking of kits containers)	(m)
L^p	Length of a pallet along the line (we assume no stacking of pallets)	(m)
L_s	Available length along workstation s	(m)
m_{is}	Number of units of part i assembled per vehicle (if the specific variant part i is used) at station s	
n_i	Number of units of part i contained in the original packaging; packing quantity of part i	
OC	Cost of labour (per hour) of an operator	(€/h)
OV	Average walking speed of an operator	(m/h)
$pack_i$	supplier packaging of part i {Box, Pallet}	
q_{is}	Yearly usage of part i at station s; $q_{is} = m_{is} f_{is} d$	
ρ^b	Expected capacity utilization of the milk run tours for boxes	

ρ^k	Expected capacity utilization of the milk run tours for kits	
R^b	Constant cost for the replenishment of one box in the supermarket	(€)
R^p	Constant cost for the replenishment of one pallet in the supermarket	(€)
τ^{bulk}	Average time to search for the required part from bulk stock at the line	(h)
τ^k	Average time to search for the required part from bulk stock in the supermarket	(h)
θ_{is}	Number of units of part i that will on average be picked in one pick when part i is kitted for station s	
v_i	Number of units of part i that a kit can maximally hold; this categorical parameter represents the volume (small, medium, large, extra large) of a part i $\{100, 20, 5, 1\}$	
V^b	Velocity of the material handling equipment for milk run tours for boxes	(m/h)
V^k	Velocity of the material handling equipment for the milk run tours for kits	(m/h)
V^p	Velocity of the material handling equipment for pallets	(m/h)
w_i	Weight of part i	(kg)
w^k	Weight constraint on one kit unit; maximum weight per kit	(kg)

Variables

K_s	Integer auxiliary variable
	Number of kits needed at stations s to assemble one vehicle

N_s^b	Integer auxiliary variable Number of facings needed to store boxes along station s (with vertical stacking of boxes)	
x_{is}	Binary decision variable $x_{is} = 1$, if part i is bulk fed 0, if part i is kitted	

Cost and Time Factors

C_{kit}	The yearly labor cost for kit assembly	(€)
C_{pick}	The yearly labor cost for operator picking at the assembly line	(€)
C_{repl}	The yearly labor cost for the replenishment of the supermarket	(€)
C_{total}	The yearly labor cost	(€)
C_{tpt}	The yearly internal transport cost	(€)
C_{tpt}^{pallet}	The yearly cost for pallet transport	(€)
C_{tpt}^{box}	The yearly cost for box transportation	(€)
C_{tpt}^{kit}	The yearly cost for kit transport	(€)
FC_{kit}	The yearly fixed cost to assemble all kits	(€)
tp_{is}^{bulk}	Average time to pick a unit of part i from a bulk container at station s	(h)
tp^k	Average time for the line-operator to pick a unit from a kit	(h)
tk_{is}	Average time for the operator in the supermarket to pick a unit from a bulk container of part i to kit for station s	(h)
VC_{kit}	The yearly variable cost to assemble all kits	(€)

Acronyms

3PL	Third Party Logistics Provider
BoL	Border of Line
CPU	Central Processing Unit
HBW	High Bay Warehouse
JIT	Just In Time
SBW	Small Box Warehouse
UL	Unit-load
VBA	Visual Basic for Applications
WIP	Work In Process
WS	Workstation

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Nederlandse samenvatting –Summary in Dutch–

In onze huidige economie heerst er sterke concurrentie tussen productiebedrijven. Bovendien zijn klanten vandaag de dag enorm veeleisend. Ze willen een snelle levering, lage prijzen en bovendien op maat gemaakte producten die voldoen aan hun individuele wensen. Om onder deze moeilijke omstandigheden te overleven en winstgevend te zijn, heeft een bedrijf nood aan een goed draaiend productiesysteem. Tot nog toe spitste onderzoek zich voornamelijk toe op het vinden van productieverbeteringen. Echter, bedrijven realiseren zich nu dat het verbeteren van de logistieke organisatie een alternatieve manier is om een concurrentieel voordeel te bekomen ten opzichte van andere marktspelers.

Material handling wordt als een hoofdzaak beschouwd omwille van het cruciale belang om de juiste materialen, op het juiste tijdstip, op de juiste plaats, en in de exacte hoeveelheid beschikbaar te hebben aan de lijn. Als er geen betrouwbaar leveringsproces is zullen er productievertragingen optreden en mogelijks zal de lijn stilgezet moeten worden. Dit laatste zal bijkomende vertragingen en extra kosten teweeg brengen. In de autoassemblage industrie specifiek is *material handling* extra belangrijk. Voertuigen hebben namelijk veel klant-specifieke opties en bijgevolg circuleren er veel verschillende onderdelen op de productievloer.

De organisatie van de onderdelenbevoorrading naar de assemblagelijnen en de stijgende complexiteit ervan in de huidige bedrijfseconomische situatie is beperkt behandeld in de literatuur. Er bestaat een aanzienlijke onzekerheid over de kosten en baten van verschillende onderdelenbevoorradingssystemen. Bovendien is er een gebrek aan onderzoek over de strategische keuze tussen verschillende werkwijzen.

In de industrie vinden we twee onderdelenbevoorradingssystemen uitgebreid terug, met name *bulk feeding* en *kitting*.

Enerzijds is *bulk feeding* de meest vanzelfsprekende manier voor het aanvoeren van onderdelen. Bij dit systeem worden onderdelen toegevoerd aan de assemblagelijn in hoeveelheden groter dan één, in een specifieke container. De containers worden dicht bij de werkstations geplaatst aan de zijkant van de assemblagelijn, en de herbevoorrading van containers gebeurt op basis van een *two-bin* systeem of op basis van een vastgelegd bestelpunt.

Anderzijds worden bij *kitting* verschillende onderdelen samen in een (heterogene) verpakking gegroepeerd, gebaseerd op een toekomstige productieplanning. Deze kits worden dan aangevoerd aan de lijn. Eén kit bevat de onderdelen voor één of meerdere bewerkingen aan de assemblagelijn, voor één enkel eindproduct. In een omgeving met veel variatie en een assemblagelijn waarop verschillende modellen achter elkaar geproduceerd worden zal elke kit anders zijn. De kits worden dan aangevoerd in de volgorde van de productieplanning op de lijn. De exacte hoeveelheid onderdelen wordt in kits dicht bij de werkstations geplaatst aan de zijkant van de assemblagelijn. Herbevoorrading van kits gebeurt op het ritme van de productiecyclustijd.

Bulk feeding en *kitting* werden eerder apart bestudeerd. Bovendien brengen sommige studies beide onderdelenbevoorradingssystemen zelfs met elkaar in verband en vergelijken hun voor- en nadelen. Niettemin is er voor zover wij weten nog nooit in de literatuur een algemeen model gepresenteerd om het keuzeproces - tussen *kitting*, gedeeltelijke *kitting*, en *bulk feeding* - te ondersteunen. Dit is het onderwerp van dit proefschrift.

Om individuele onderdelenfamilies toe te wijzen aan één van de twee onderdelenbevoorradingssystemen werd een *mixed integer linear programming model (MILP)* ontwikkeld. De doelfunctie van het model is het minimaliseren van de totale kosten, gegeven de onderdelenkarakteristieken en de productmix. Het is een statisch en deterministisch optimalisatieprobleem, waarbij de kosten bestaan uit gemiddelde jaarlijkse personeelskosten voor picking aan de lijn, intern transport, kit assemblage, en herbevoorrading van de supermarkt. Het basismodel is beschreven in Hoofdstuk 2, terwijl een uitbreiding is voorgesteld in Hoofdstuk 4. Het finale model heeft aangetoond dat de interne logistieke kosten voor *kitting* - dat zijn de kosten gemaakt tussen het magazijn en het *use-point* aan de lijn - hoger zijn dan de interne logistieke kosten voor *line stocking*. *Kitting* is op logistiek vlak een duurdere oplossing omdat onderdelen allereerst behandeld worden door de *kitting* operator, voor ze getransporteerd worden naar de lijn. Ze worden dan een tweede maal behandeld door de operator aan de lijn.

Deze *double-handling* wordt vaak aanzien als verspilling en is het hoofdargument van tegenstanders van *kitting*. Echter, op het niveau van assemblage heeft *kitting* een enorm voordeel aangezien de voorraad aan de lijn beperkt wordt. Daardoor is de *border of line* minder druk bezet en kunnen de wandelafstanden van de operators ingekort worden. De efficiëntie aan de lijn is daardoor hoger. Bijgevolg toont het model aan dat *kitting* tot op zekere hoogte voordelig is. Niet alleen de wandelafstanden van de operator naar onderdelen in kits zijn ingekort, maar ook de wandelafstanden naar de onderdelen die nog overblijven in bulk zijn korter door de daling in voorraad aan de lijn. Om te voorkomen dat de hoge logistieke kosten van *kitting* de voordelen in operator efficiëntie teniet doen moeten de onderdelen die gekit worden met zorg geselecteerd worden.

Omwille van het nieuwe karakter van het probleem behandeld in dit proefschrift, zijn er geen probleemvoorbeelden beschikbaar uit de literatuur. In Hoofdstuk 3 wordt een gevalstudie van een bedrijf in de autoassemblage industrie beschouwd. De verzameling van onderdelen is bestudeerd en typerende kansverdelingen zijn opgesteld. Op basis van deze kansverdelingen werd een algoritme ontwikkeld voor het creëren van realistische synthetische datasets.

In Hoofdstuk 5 worden experimentele resultaten besproken. Eerst en vooral hebben we de invloed van onderdeel- en productmixkenmerken op de beslissing om al dan niet te kitten bestudeerd. Het werd aangetoond dat bepaalde individuele onderdelenkenmerken sterk beïnvloeden of een onderdeel geschikt is voor *kitting* of niet. Vijf hypotheses werden getest en bevestigd. In de eerste plaats blijken onderdelen die veel plaats innemen in een kit minder snel gekit te worden. Ten tweede worden onderdelen die behoren tot grote onderdelenfamilies wel vaak gekit. Ook onderdelen die oorspronkelijk in palletten verpakt zijn hebben een hoge kans op *kitting*. Bovendien hebben ook onderdelen met een hoge waarde voor θ_{is} een hoge kans op *kitting*. Tenslotte is het voor onderdelen met een hoog (jaarlijks) verbruik q_{is} minder voordelig om te *kitten*. Naast individuele onderdelenkenmerken benadrukken we dat ook de mix van onderdelen een grote invloed uitoefent op de oplossing. In sectie 5.2 is een *design of experiments* opgezet om de impact van bepaalde *kitting* parameters te onderzoeken.

Ten slotte presenteert Hoofdstuk 6 enkele conclusies en worden er suggesties voor toekomstig onderzoek gegeven.

English Summary

Manufacturers nowadays are confronted with highly demanding customers and fierce competition. To cope with these difficult circumstances, they need to have a competitive production organism. Until now research has been dealing abundantly with production improvements but companies today realize that improving their logistics organization is an alternative opportunity for obtaining an advantage over their competitors.

Material handling is seen as a core issue because of the major importance for production to have the right materials, at the right time, at the right place, and in the exact amount at the line. If a reliable supply process is not in place, production delays will occur and possibly the line must be stopped which involves additional delays and consequently extra costs. In the automotive industry specifically the need for efficient material handling is preponderant because vehicles are much customized and as a consequence a lot of variant parts move around on the shop floor.

The organization of material supply to assembly lines and the growing complexity of it in current circumstances have been scarcely dealt with in literature. Considerable uncertainty still exists concerning the costs and benefits of the alternative supply methods. Moreover, research about the strategic choice between different materials supply systems is lacking.

Two materials supply methods that are abundantly found in industry are bulk feeding and kitting.

On the one hand, bulk feeding - sometimes also referred to as line stocking, continuous replenishment, or point-of-use storage - is the most straightforward method of materials supply. Under this system, parts are supplied to the assembly line in quantities larger than one, within a dedicated container. Containers are stored close to the assembly workstations at the border of the line, and a two-bin or reorder point system is used to control replenishment.

On the other hand, kitting systems group together various components into one (heterogeneous) package according to a future assembly schedule and supply these kits to the line. A kit then supports one or more assembly operations for one given end product. Especially in a high variance mixed-model environment every kit will be different and kits will be sequenced according to the future assembly schedule. The exact quantity of components required is stored in kit containers close to the assembly workstations at the border of the line, and replenishments are carried out according to the assembly schedule which is based on the assembly cycle or takt time.

Bulk feeding and kitting have been studied separately. Moreover, some studies relate both materials supply methods and compare their advantages and disadvantages. Nevertheless, to the best of our knowledge no general purpose model that would facilitate the selection process - between kitting, partial kitting, and line stocking (i.e. no kitting) - has been reported in literature. This is the topic of this dissertation.

A mixed integer linear programming model (MILP) is developed to assign individual parts to one of both materials supply system alternatives to minimize the total costs, given the average part and production mix characteristics. This is a static and deterministic optimization problem, where the costs are the average yearly labor costs for operator picking at the line, internal transport, the kit assembly operation and replenishment of the supermarket. The base model is presented in Chapter 2, while an extension is discussed in Chapter 4. The final model has shown that the in-plant logistics costs for kitting - i.e. the costs of the material flows from the warehouse to the use-point at the line - are more expensive than the in-plant logistics costs for line stocking. Kitting is logistically a more expensive solution since material is handled by the kitting operator, before it is transported to the line. It is then handled a second time by the operator at the line. This double-handling has often been seen as a waste and is the main argument of the opponents of kitting. However, with regard to assembly, kitting has a major advantage in reducing the amount of inventory at the border of the line. Since the border of the line becomes less crowded, the walking distances of the operators decrease and operator efficiency increases. As a consequence the model demonstrates that kitting to a certain degree is beneficial. Not only operator walking distances towards parts within kits are reduced, but also the walking distances towards the remaining parts in bulk are shortened due to the reduction in stock at the border of the line. To prevent the high in-plant logistics costs of kitting from canceling out the gain in operator efficiency at the line, the parts that are kitted must be selected with care.

Due to the novelty of the problem, no problem instances are available in literature. In Chapter 3, a case study at a company in the automotive industry is considered. The collection of parts is studied and characteristic distributions are generated. Based on these distributions, an algorithm is developed for the creation of realistic synthetic part datasets.

In Chapter 5, computational results are discussed. In the first place, the impact of part and product mix characteristics on the decision to kit or not to kit is examined. It is demonstrated that some individual part characteristics considerably influence if a part should be kitted or not. Five hypothesis are tested and confirmed. Firstly, the parts that have the least tendency to be kitted are the parts that take up a lot of space in a kit. Secondly, the parts that have a higher chance to be kitted are parts that belong to a large part family. Moreover, the parts that have a higher chance to be kitted are parts that are originally packaged in pallets. Furthermore, the parts that have a higher chance to be kitted are parts that have a higher θ_{is}. Finally, the parts with a higher (yearly) usage q_{is}, have a lower probability to be kitted. Aside from the individual part characteristics it is also emphasized that the mix of parts exerts a great influence on the solution. In section 5.2, a design of experiments is set up to study the impact of certain kitting parameters on the solution.

Concluding comments and suggestions for further research are presented in Chapter 6.

1

General Introduction

Nowadays, customers put a lot of pressure on the market to obtain timely delivery and low prices. In addition, more and more variation in the assortment is demanded and custom-made products are often requested. This current trend is explicitly perceivable in the automotive industry. Increasingly, automotive manufacturers are aiming for mass customization - providing such a variety of products that nearly everyone can find what they want (Alford et al., 2000). Each single vehicle that comes off the line is different and is equipped with the proper options requested by the customer. This evolution towards more customization has major consequences for production organizations and their logistics departments. As a matter of fact, components do not only exist in one variant but alternative variant parts may have to be assembled. This leads to an increasing number of parts moving around on the shop floor and undoubtedly to a more complicated material supply process.

The main task of a good materials supply method is to supply the right materials, at the right time, to the right place, and in the exact amount to the line for production to take place. In order to be competitive in industry, it is important that this supply process is executed in a cost-effective manner. However not only the cost of supplying the parts, but also the impact on the assembly operations should be considered. Different line feeding systems will have an influence on how the parts will be displayed at the border of the line. Moreover, the available space at the border of the line is mostly constrained. Figure 1.1 represents an assembly line with the inventory lined up along the border of the line. At the back of the line stock a forklift truck is passing with a pallet to resupply a station.

In industry, one can find different materials supply systems. The most straightforward method of materials supply is line stocking, sometimes also referred to as bulk feeding, continuous replenishment, or point-of-use storage. Under the line stocking system, parts are supplied to the assembly line in quantities larger than one, within a dedicated container. Containers are stored close to the assembly workstations at the border of the line, and a two-bin or reorder point system is used to control replenishment. In a two-bin system a new order is placed when the first bin is used up. The second bin then covers the delivery lead time and provides a safety stock. Before the second bin is depleted the new order will have arrived. Instead, in a reorder point system a new order is placed when the inventory level of the item signals the need for replenishment. The reorder point inventory level takes into account the consumption of the item during the delivery lead time and the quantity required as safety stock. The inventory will suffice until the new order arrives.

Besides straightforward line stocking, sometimes parts are first repackaged from the large containers they arrive in into smaller bins before they are supplied to the line. This materials supply system is called downsizing.

A third method of line feeding is sequencing. Sequencing parts means that the parts are not stored in bulk at the border of the line but are only supplied to the line at the moment and in the quantity they are needed according to the assembly schedule.

Finally, parts can also be grouped together into kits before they are supplied to the line. A kit then supports one or more assembly operations for one given end product. Especially in a high variance mixed-model environment every kit will be different and kits will be sequenced according to the future assembly schedule. The exact quantity of components required is stored in kit containers close to the assembly workstations at the border of the line and replenishments are carried out according to the assembly schedule which is based on the assembly cycle or takt time.

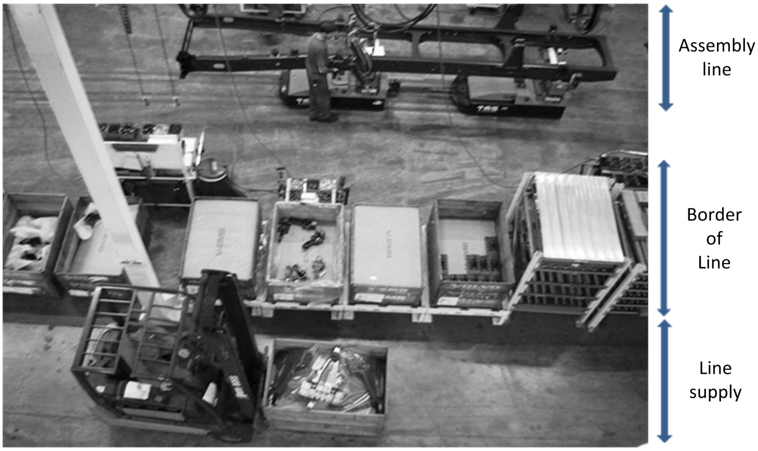
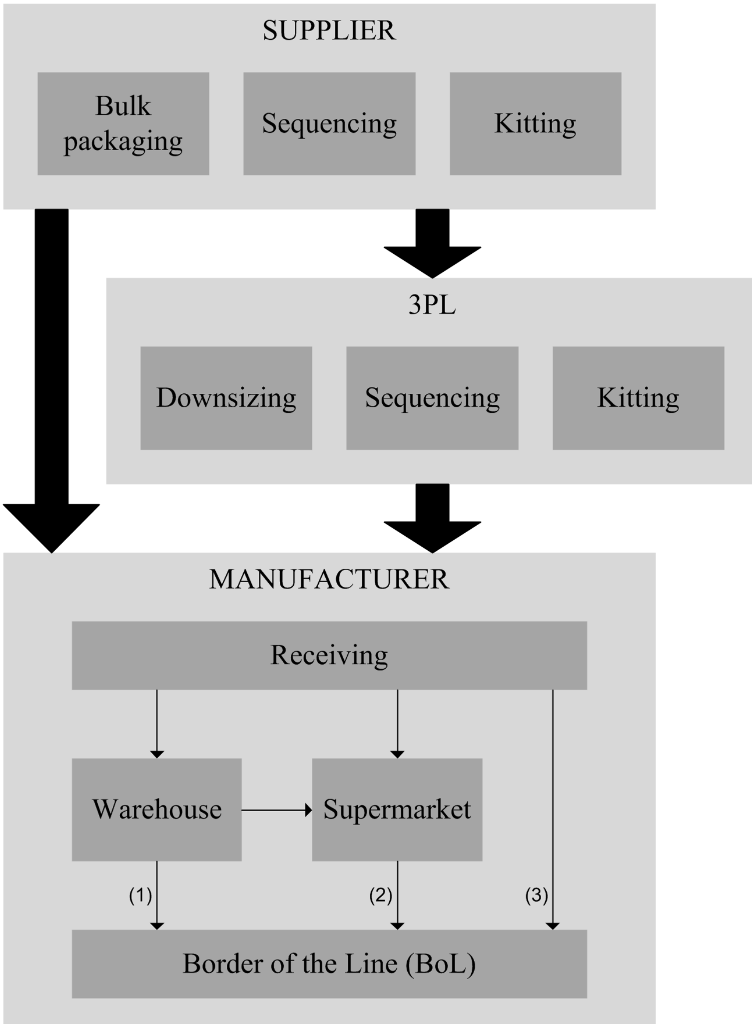


Figure 1.1: *Picture of a typical assembly line with line stock*

Downsizing, sequencing and kitting induce additional material handling activities that can take place at different points in the supply chain. The supplier can, immediately after production, package the parts in bins that are preferred by the manufacturer, or he can sequence parts, or combine them into kits. Likewise the parts can be repackaged, sequenced or kitted once they are received at the manufacturing plant. In that case an additional material handling step takes place in between the receiving area and the use-points at the assembly line, in so-called supermarkets. Finally, if neither the supplier, nor the manufacturer wants to do the additional material handling a third party logistics provider (3PL) can be hired to prepare the parts for the desired supply. Of course many considerations enter into this decision, an important one being the relative location of the parties involved. Figure 1.2 represents the basic flows of material for the different supply systems.

Each of the materials supply systems discussed above are found in practice, and each of them offers certain operational benefits and disadvantages. However, little research has been carried out to gain insight into the different materials supply methods and the trade-offs between them. Companies' decisions are mainly based on intuition and experience but no objective knowledge exists about the advantages and disadvantages of the different systems. Figure 1.3 illustrates the display of parts at the border of the line for each of the different materials supply systems. It can be seen immediately that a shift away from line stocking will diminish the stock at the border of the line. This will reduce operator walking during assembly. Moreover,



(1) Line stocking
(2) In-house downsizing/sequencing/kitting
(3) Outsourced downsizing/sequencing/kitting

Figure 1.2: *Flow of material for the different line feeding methods*

searching times will be eliminated if parts or kits are sequenced according to the production schedule.

Although limited research on the different line feeding systems has been carried out until now, the request for an increased knowledge on the subject of line feeding is more present than ever before. With increasing cost competition and product variety, providing an efficient just-in-time (JIT) supply has become one of the greatest challenges in the use of mixed-model assembly line production systems (Boysen and Bock, 2011).

1.1 Literature Review

The part supply of mixed-model assembly lines is a largely unexplored field of research (Boysen and Bock, 2011). In this section we will give an overview of the current state of the art.

1.1.1 Operational Control and Performance Measurement of Part Feeding Systems

Some studies focus on issues concerning the implementation of materials supply methods in practice. Chen and Wilhelm (1993, 1994, 1997) and Chen (2003) extensively study the problem of allocating a limited amount of available components to different kits that demand these components. They develop an optimal algorithm for the basic problem and compare two heuristics commonly used in industry with a newly developed heuristic. In addition, they add the assumptions of parts being substitutable and linked substitution to the problem. All of their models are developed to minimize total costs - including job earliness, job tardiness, and in-process holding costs. Choobineh and Mohebbi (2004) look at the positive effect of component sharing on kit availability, given that there is considerable uncertainty in the environment. The uncertainty can be associated with variability in the procurement lead times of the components, or with the varying demand.

Brynzer and Johansson (1995) discuss a number of case studies in order to get more insight into the design of kitting systems and the influence on performance. Some issues discussed are the location of the kitting system, the work organization behind the kitting operation, the relevance of a batching policy for picking the kits, the need

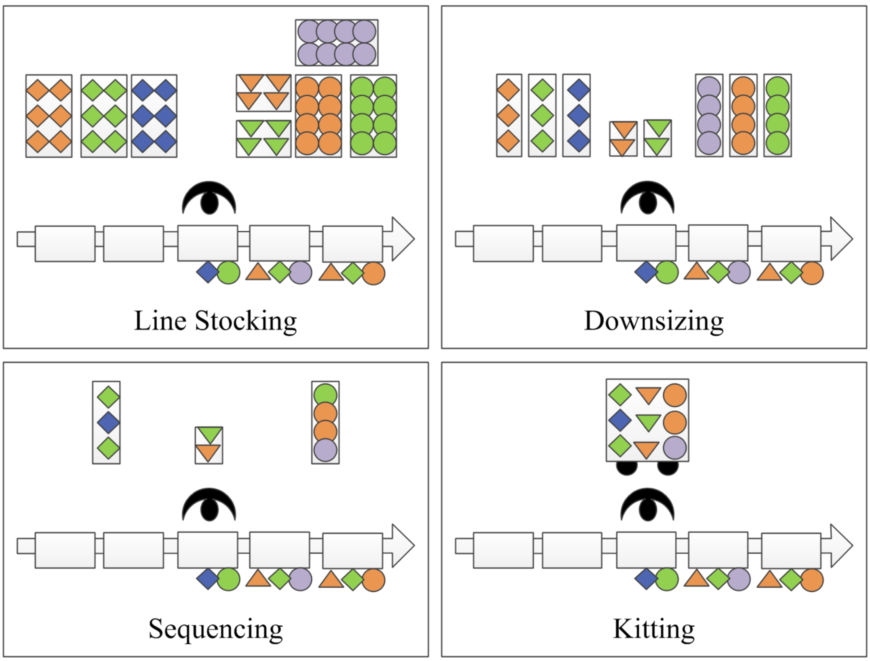


Figure 1.3: *Impact of different line feeding methods on the display of parts at the border of the line.*

for zone picking and the type of picking information used.

Kitting is also studied in relation to ergonomics. On the one hand the materials kit functionality is considered and the insight is gained that assembly work is definitively supported by the materials kit configuration (Medbo, 2003). On the other hand, two alternative methods for materials kitting - i.e. picker-to-material and material-to-picker - are compared with regard to muscular activity, work postures and movements (Christmansson et al., 2002). The material-to-picker method showed improved productivity and low levels of physical exposure with respect to muscular activity and work postures.

Furthermore, kitting systems are approximated analytically. Theoretical derivations were shown for kitting operations with two inputs. Som et al. (1994) and Ramachandran and Delen (2005) present results about the work-in-process and the output of kitting operations that are subject to uncertain supply. De Boeck and Vandaele (2008) analyze the coordination of material from two independent suppliers, which is then assembled in an assembly facility. Results are derived for two performance measures, i.e. the synchronization time of the components and the inter-arrival time of the kits. Ramakrishnan and Krishnamurthy (2008) go further and consider kitting systems with multiple inputs. They introduce analytical approximations and the throughput estimate is used to compute other performance measures of interest such as mean queue length and mean waiting time in the system. De Cuypere and Fiems (2011) study the impact of production interruptions on kitting.

A model for the assembly line feed problem in bulk containers is proposed by De Souza et al. (2008). This model decides how to pack the necessary items in the available containers. The model strives to minimize holding and handling costs while considering among other things the availability of containers and the demand that must be met. The authors propose an integer programming model as well as a heuristic to solve the problem.

Other authors focus on the delivery of containers to the line. Boysen and Bock (2011) consider the scheduling of part supply in bulk to mixed-model assembly lines. A model is determined to sequence boxes to feed the line and the objective function pursues the minimization of the maximum inventory level in all stations over all cycles of production. The model allows to weigh inventory of different parts differently according to part-dependent characteristics as part dimensions or values. As a material shortage at a station would be extremely costly due to a resulting line stoppage or off-line repairs, the resulting sequence has to guarantee that no station may run out of parts. The problem proposed is proven to be NP-hard and different exact and heuristic solution procedures are proposed. Golz et al. (2010) discuss the supply by means of an internal shuttle system which supplies the various stations with the needed parts. Their main objective is to minimize the required number of shuttle drivers to obtain a timely supply. They developed a heuristic solution procedure to solve the problem.

Finally, Klampfl et al. (2006) addresses the issue of workstation layout optimization. The problem is defined as the allocation of stock within work cells in order to minimize non-value added operations, such as walking and waiting. They discuss three optimization problems. Firstly, they propose an unconstrained problem where all the bins are assumed to be at the minimum allowed distance from the moving line. With this formulation there is no guarantee that in the solution, different bins will be spaced so as not to overlap and there is also no guarantee that all the variables will fall within the boundaries of the workcell. Next they propose a one-dimensional constrained problem that guarantees that the workcell elements do not overlap in the x-direction and are completely contained in the workcell. Finally they present a two-dimensional constrained problem which guarantees that if the part bins overlap in the x direction, they do not overlap in the z direction and vice versa; in other words, there is no physical overlap of the workcell elements. For solving the unconstrained problem they use the Downhill Simplex Method; for the one-dimensional constrained problem they use Sequential Quadratic Programming; for the two-dimensional constrained problem they use a branch and bound method based on Sequential Quadratic Programming. The methods suggested by Klampfl et al. (2006) can be used in practice in the context of a tool called e-Workcell (Gusikhin et al., 2003; Klampfl, 2004).

1.1.2 Advantages and Disadvantages of Different Part Feeding Systems

Whereas the above studies concentrate on operational control and performance improvement of a materials supply system in place, we are interested in the deliberate choice of a certain materials supply system. Several authors report on the benefits and drawbacks of the different part supply systems. We will focus on discussing the advantages and disadvantages of the two most extreme methods of line feeding - kitting and line stocking. These two materials supply systems are opposite in a way that benefits of one system are drawbacks of the other system, and vice versa. Downsizing and sequencing are more moderate line feeding systems, therefore inheriting some of the advantages and disadvantages of kitting and line stocking in a more subtle way.

One of the major advantages of kitting is the reduced stock of parts at the border of the line. Whereas in the situation of line stocking full materials containers, with numerous identical components in the same container, are stored at the border of the line, in the situation of kitting this stock is minimized by storing only few kits at the line. Especially in a situation of mass customization this is an important advantage, as the need to have a huge amount of different variant parts at the line would lead to an enormous plant if all parts are to be stored at the border of the line (Medbo, 2003). Swaminathan and Nitsch (2007) refer to this as *space feasibility*. Variants required must be displayed at or near the workstation where they will be installed. Keeping sufficient inventory for a large number of variants can require too much space near the final assembly line, compromising the space feasibility. This can be because of the size of the component itself, e.g., seats, or the large number of variants, e.g., cowl-wire harnesses. In case of a problem of space feasibility, kitting can be a solution.

Moreover, the reduction of work-in-process (WIP) has a positive effect on parts visibility and accountability on the floor (Bozer and Mcginnis, 1992). The number of kits provide immediate information regarding the WIP level, since each kit consists of a predetermined quantity of parts, and this leads to an improved control over the work-in-process (Ding and Puvitharan, 1990; Ding, 1992; Choobineh and Mohebbi, 2004). Especially for high cost and/or perishable components this is a valuable advantage (Bozer and Mcginnis, 1992). Consequently, the majority of the material is stored centrally which increases security in the control of physical inventory and which allows for reduction of inventory at a given service level (Caputo and Pelagagge, 2008).

Aside from the benefits of a reduced inventory at the border of the line, this also has some drawbacks. In case a part in the kit is wrong, defective or simply missing, production will be disrupted. Unlike in the case of line stocking where another part can be taken directly out of the container, in the case of kitting no safety stock is available at the line. A replacement part must be brought in from the central storage area. Components that may fail during (or as a result of) the assembly process, will also require special consideration or exceptions (i.e. they may have to be excluded from the kits) (Bozer and Mcginnis, 1992). As a component stock-out during the assembly process is one of the most undesirable events that can occur - since the resulting line stoppage is associated with extremely high costs (Bukchin and Meller, 2005) - one may be forced to provide either spare parts or to store component containers at some workstations (Bozer and Mcginnis, 1992).

The savings in manufacturing floor space have an additional important advantage in reducing the walking distances for the assembly operator to retrieve parts, thus reducing the overall materials handling time at the work station. Therefore, kitting is often advised under a Lean philosophy. Lean manufacturing is a practice that puts customer focus above all and aims at eliminating all wasteful activities in order to create maximum added value. In this regard, kitting helps to remove all waste from the value adding assembly operation and lead times toward the customer can be shortened.

Not only are operator walking distances reduced under a kitting system, productivity is also improved for other reasons. For one thing, search times to look for the correct parts to be assembled are completely eliminated in the case of kitting. Operators simply will not need to search for the required parts as all needed parts will be presented in one or more kits (Ding and Puvitharan, 1990; Ding, 1992). Next, since components are usually placed in their proper positions inside a kit container and parts are also often ideally prepositioned, assembler's work is even more supported and picking times are further reduced (Bozer and Mcginnis, 1992; Caputo and Pelagagge, 2008). Accordingly, the time required to assemble units can be shortened and production workers and machines can be used more efficiently. The materials in a kit may also be used as a work instruction (Wanstrom and Medbo, 2009) and this will ease education of new staff (Ding and Puvitharan, 1990). Consequently training costs will be reduced (Ding and Puvitharan, 1990; Medbo, 2003). Swaminathan and Nitsch (2007) refer to *selection feasibility* to explain that the operator must be able to handle the selection complexity, e.g. decoding the specifications sheet and remembering the required part picks. Controlling the exact quantity, position and orientation of individual parts placed in a kit container then also offers an opportunity to implement robotic handling (Bozer and Mcginnis, 1992). Medbo (2003) defines this usefulness of materials kits in respect of operators' handling of materials and cognition during assembly work as "materials kit functionality".

In some cases, a kit may actually resemble a "loosely assembled" product (Bozer and Mcginnis, 1992). Aside from the increase in workstation productivity this entails, this also offers potential for increase in product quality. Given that the kit package is properly designed, it would be easy to notice if a component is missing (Schwind, 1992). Quality checks will take place earlier in the value chain and it will be possible to reduce the frequency of wrong or missing parts in the end product (Carlsson and Hensvold, 2008). For components that look alike, the risk of assembling the wrong part is eliminated as the operator does not need to look for the correct component anymore. Furthermore, it is avoided that parts are lying idle in open packages at the border of the line, minimizing the risk of damage (Schwind, 1992).

When rebalancing a line, *cycle time feasibility* (Swaminathan and Nitsch, 2007) is an important concept. The operator must be able to install the different variants within the time available. The improved productivity at the line under a kitting system will then, ceteris paribus, result in shorter feasible cycle times.

Contrary to kitting systems, line stocking systems have more stock at the border of line. Operator walking distances will be longer and some time will be needed to search for the correct part. This will also create a risk of picking and assembling the wrong parts. Furthermore, large containers might jeopardize ergonomic conditions at the workstations. Finnsgard et al. (forthcoming) carried out a study to compare the ergonomics conditions for the assembly operator where components are exposed in wooden pallets versus smaller bins. The ergonomics conditions improved greatly, with a 92% reduction of potentially harmful picking activities, thereby almost eliminating potentially harmful body movements.

Besides the benefits of kitting at the line, kitting brings about double handling of parts. Kit preparation consumes time and effort, with little or no direct value added to the product (Bozer and Mcginnis, 1992). The kit preparation also increases space requirement in the stockroom (Caputo and Pelagagge, 2008). In addition, an increased number of handling occasions increases the probability of damaging the components. Therefore, not all components are suitable for kitting (Johansson and Johansson, 2006).

With regard to internal transport, kitting facilitates material delivery to workstations by eliminating the need to supply individual component containers (Bozer and Mcginnis, 1992). Since kits are consumed in sync with the takt time, it is easier to schedule kit replenishments than to schedule bulk replenishments, potentially improving material handling system efficiencies. Better streamlining of component-flow on the shop floor is possible (Choobineh and Mohebbi, 2004) and there will be less damage in the transportation process (Corakci, 2008). Additionally, the density of kits will have a major effect on the efficiency of transport. In general, we expect the density of kits to be lower than the density of bulk containers.

Furthermore, kitting as an alternative for line stocking has an important impact on manufacturing flexibility. Kitting requires that a production sequence is determined beforehand. Kits will then be assembled based on the exact needs from production. On the one hand, this means the actual production sequence must be known long enough in advance, so that sequenced delivery from the kitting area can take place in time. Swaminathan and Nitsch (2007) define *information lead time* as the time available between the communication of the actual build sequence and the installation of the part on the final assembly line. A feasible *information lead time* depends on the available stock at the line and on the transportation time to the line. However, the required flexibility at the final manufacturing plant must be considered as well. Often, it is necessary to resequence vehicles because of paint defects or parts shortages for certain variant combinations (Swaminathan and Nitsch, 2007). If there is a schedule change, the whole kit may have to be returned and de-kitted so that its parts are available for other assemblies (Carlson et al., 1994). To keep track of part usage and correct inventory levels, it is necessary to accurately check and count parts in the kits that are returned. On the other hand, kitting allows checking beforehand if all needed parts are available. If there are shortages, a new order can be set at the supplier, or the sequence can be changed deliberately to avoid problems at the line. Because inventory is not distributed on the shop floor, setups and changeover times are reduced, i.e. obsolete materials can be readily removed from the inventory (Caputo and Pelagagge, 2008).

Finally, the success of kitting depends a lot on the quality of the execution. Firstly, kitting demands additional planning to assign on-hand parts to kits, especially when kits contain several common components. An assignment of available parts to kits needs to be done (Bozer and Mcginnis, 1992). Temporary shortage of parts may force the user to kit short and doing so will reduce the overall efficiency of the operation, due to the double-handling of the kit containers and the additional storage space required by partly assembled kits (Bozer and Mcginnis, 1992). Secondly, as already mentioned, errors in kit preparation will interrupt production due to a lack of safety stock at the line. Moreover, this may lead to some kits being *cannibalized*. That is, short parts may be removed from some of the next available kits in sequence, and later when a new shipment is received the parts are again added to the *cannibalized* kits. This may further complicate the shortage and it may lead to problems in parts accountability (Bozer and Mcginnis, 1992). Besides, this is again an activity of double-handling, and this will obviously harm efficiency of the kitting system. Nevertheless, from a Lean point of view the sensitivity of a kitting system to mistakes is a good thing, because exposing mistakes is the only way to deal with them thoroughly.

We now discussed the advantages and disadvantages of kitting and line stocking. In Table 1.1 a summary is shown.

Next to line stocking and kitting, downsizing moderately combines some characteristics of both. In fact, downsizing is a form of line stocking - with smaller containers at the line - inheriting some of the benefits and drawbacks of kitting in a less outspoken way. Likewise, the stock at the line is also reduced and walking distances are therefore shortened. However the decrease in stock and walking distances is less extreme as compared to kitting. Inventory along the line will be more limited and this leads to better visibility and control of WIP. No production sequence needs to be determined beforehand and there is still some safety stock at the line. Nevertheless, some additional material handling is needed to repackage parts to smaller bins. Internal transport is still organized based on a pull system and variability in demands lead to peaks and drops in transport requirements.

Finally, sequencing basically is a form of kitting - with only one part reference per kit. Sequencing can easily be done by the supplier because parts from different suppliers do not have to be collected in one kit container. Supplying parts to the line is only influenced by the availability of the part concerned, whereas with kitting the supply of kits depends on the availability of all parts in the kit and a late delivery of just one supplier may derange everything. At the same time, every single part needs to be supplied to the line separately. By forming denser kits, a gain in internal transport costs may be obtained.

Table 1.1: *Advantages and disadvantage of kitting and line stocking*

	Line stocking	**Kitting**
Manufacturing productivity	(-) long operator walking distances	(+) reduced operator walking distances
	(-) operator search times	(+) elimination of operator search times
		(+) reduced picking times thanks to prepositioning
		(+) kit functions as a work instruction
	(-) longer cycle times	(+) shorter cycle times can be realized
	(-) large containers negatively impact ergonomics	(+) improved ergonomic conditions
Border of line (BoL)	(-) excessive stock at the BoL	(+) reduced stock at the BoL
	(-) great manufacturing space requirement	(+) reduced manufacturing space requirement
	(-) bad control over WIP	(+) improved parts visibility and improved control over WIP
Material handling	(+) elimination of non-value adding material handling activities	(-) kit preparation consumes time and effort and is non-value adding
		(-) increased space requirement in the stock room; a kitting area is needed
		(-) an increased number of handling operations: increased probability of damaging parts
		(+) material is stored centrally: increased control and reduction of inventory at a given service level
		(-) kitting demands additional planning

Table 1.1: *Advantages and disadvantage of kitting and line stocking (continued)*

	Line stocking	**Kitting**
Internal transport	(-) variable material flows of individual containers (pull)	(+) control over materials flows of kits: synchronization of transport with takt times; simplified material flow and less damage
	(+) component containers are often denser than kit containers	
Quality	(-) risk of picking and assembling the wrong parts	(+) increase in product quality as the operator does not need to search for right parts
	(-) higher risk of damaging parts at the line	(+) parts are not lying idle in open packages at the line
	(+) safety stock at the line to replace defective parts	(-) errors in kit preparation: production will be interrupted or other kits may be cannibalized
	(-) if a shortage is detected too late, missing parts may cause production interruption	(+) quality checks earlier in the value chain
		(-) Temporary shortage of parts may force the user to kit short and doing so will reduce the overall efficiency of the operation
Flexibility	(-) product changeover is time consuming	(+) Product changeover is simplified
	(+) safety stock available at the line to respond to a schedule change	(-) If there is a schedule change, the whole kit may have to be returned and de-kitted
	(-) Kitting requires that a production sequence is determined beforehand	

1.1.3 Decision Models for Part Feeding

The purpose of this thesis is to analyze the strategic choice between different line feeding methods by means of a mathematical cost model. The few existing models guiding this system choice decision have a number of limitations. We will now discuss the existing models and their shortcomings in order to demonstrate the research gap.

Bozer and Mcginnis (1992) were the first to introduce the problem of choosing between kitting and line stocking. They propose a first descriptive model for decision making at an early decision stage. The model facilitates a quantitative comparison between various kitting plans and line stocking, based on multiple criteria. The performance measures employed are the necessary storage and retrieval of component containers, the flow of component and kit containers, the shop floor space requirements, and the average work-in-process. The authors emphasize the preliminary nature of their model and encourage further research in the field.

Carlsson and Hensvold (2008) adapt the previous model of Bozer and McGinnis and apply it to a real situation in the vehicle manufacturing industry, at Caterpillar. To optimize for the multiple criteria, the authors employ an Analytic Hierarchy Process technique. Hybrid policies are examined, but no theoretical basis is applied for defining a sound strategy.

Further elaborations of the model are done by Caputo and Pelagagge (2008, 2011). They distinguish between line-stocking, kitting and Kanban-based supply. An ABC-analysis is used as a basis for developing hybrid policies. No theoretical foundation for the proposed choices is given either.

Battini et al. (2009) plead for an integrated approach to component management optimization. They consider the centralization versus decentralization decision of components and the right feeding policies in one comprehensive framework. We agree that an integrated approach will be needed but in this dissertation we focus on the problem of optimizing feeding policies, given a centralized storage policy. In our opinion it is important to solve the problem of selecting the feeding pattern (bulk versus kitting) first, which will then serve as sub-problem for the larger supply chain design problem. Battini et al. take into consideration three assembly line feeding systems, i.e. pallet to work station, trolley to work station and kit to assembly line. The first system represents a line stocking policy, whereas the latter two only supply the required items to the line (kitting). The model includes different costs in handling, picking and transport activities. In contrast to our study, the focus is on multi-model assembly lines instead of high variation mixed-model lines. Part characteristics are furthermore not taken into account and hybrid feeding policies are not considered. Instead a multi-factorial analysis is proposed for the determination of one optimal feeding system for the complete line.

Hua and Johnson (2010) concede that since the introduction of the problem of deliberately choosing between kitting and line stocking by Bozer and Mcginnis (1992), still little research addresses which system is best to use in particular environments, or the factors that determine this choice. Moreover, some authors emphasize that their research shows kitting to be superior to line stocking (Ding, 1992) while other research shows just the opposite (Field, 1997; Henderson and Kiran, 1993). Further research is therefore needed to understand the trade-off between both systems. Hua and Johnson (2010) confirm the need to incorporate part characteristics into a decision procedure.

1.2 Contribution

After having defined the research gap, we now want to set our research objectives and define our research questions. In this research we want to answer some of the research issues introduced in the recent article of Hua and Johnson (2010). In the first place, we want to focus on the two opposite systems of line feeding, namely line stocking and kitting. These opposite systems have very distinct characteristics and we want to get insight into the choice of one system over the other. Secondly, we will focus on line feeding specifically within the factory walls. We will zoom in on Figure 1.2 to focus on parts that arrive in bulk at the manufacturer. For these parts a decision has to be made to supply them as such to the line, or to combine them into kits before delivery to the workstation.

This Ph.D. study encompasses three major objectives. The first is to explore the costs and benefits involved for line stocking on the one hand and kitting on the other hand. The second is to develop a cost model to find an optimal allocation of parts to the different materials supply methods. Finally, the third aim is to use the cost model to examine how part and plant design characteristics will affect the costs and the optimal allocation.

1.2.1 Contribution to the Scientific Body of Knowledge

Until now, descriptive models have only been used to analyze the results of some proposed policies. Like that, some policies can be determined that are superior to other policies. However, there is no guarantee of optimality. None of the existing models can be used in themself to obtain an optimal solution. In this research we want to develop a mathematical optimization model to fill this gap. The optimal policies coming out of the model can then be analyzed in order to improve our understanding of the problem. Our main research question is defined.

> ***General research question:***
> *Can we gain insight into the factors that determine the optimal assignment policies of parts to an appropriate material supply method - kitting or line stocking?*

Little is known about the impact of kitting and line stocking on the inbound logistics processes and on manufacturing. With our research we add to a further understanding of the different material flows. Overall, we add scientific knowledge by providing a comprehensive view of the different aspects of line stocking and kitting within one research design, and by testing it in an empirical setting.

The main research question can been subdivided into some specific research questions.

> ***Research question 1:***
> *What are the costs and benefits associated with kitting and line stocking?*

In order to develop a model that can serve as a basis for decision making, first of all a clear idea needs to be obtained of the costs and benefits involved for the different materials supply systems. The material flows for each system need to be studied and cost formulations need to be developed.

> ***Research question 2:***
> *Can we solve the cost model to optimality in order to assign all stock keeping units to a certain method of line feeding in an overall cost-effective way?*

Based on the cost formulations, an optimization model needs to be developed in order to do the assignment of parts to their most appropriate line feeding method. Consequently this model needs to be solved. Once a model is available, it can be used to investigate the solution and to do extensive testing.

Research question 3:
How do part and product mix characteristics influence the choice of the appropriate line feeding method?

Sensitivity analysis should be performed to investigate the impact of characteristics of the parts and production mix on the solution. The purpose of these analyses is building a theoretical basis for hybrid materials feeding policies, where some parts are kitted and others are fed to the line in bulk.

Research question 4:
How do plant design characteristics and kitting organization influence the choice of the appropriate line feeding method?

Sensitivity analysis should be performed to investigate the impact of plant design and the organization of the kit preparation on the solution. Thus, the additional costs or benefits of changing certain parameters can be predicted.

1.2.2 Relevance for Industry

This research emanates from a wide interest from industry to better understand the trade-offs between different line feeding systems. In practice, kitting and line stocking are both found in a lot of production organizations. Nevertheless, considerable uncertainty still exists concerning the costs and benefits of these supply methods.

In the vehicle industry particularly parts handling is currently a hot topic. Industry players understand the importance of performing their parts handling activities efficiently because a large number of transactions occur and therefore a lot of money is involved. To give an idea, we state in Table 1.2 the average number of transactions involved for a typical player in respectively the car, truck and tractor industry.

Table 1.2: *Parts handling volumes for a typical OEM in the car, truck and tractor industry*

	Number of parts in one end product	Sales/year (units)	Number of transactions/year
Cars	2500	300,000	750,000,000
Trucks	2000	25,000	50,000,000
Tractors	3000	33,000	100,000,000

Companies nowadays make a very intuitive decision on which parts to kit or not to kit. Because of the numerous parameters involved in this decision, this is certainly not an easy task.

This research has a strong managerial impact and an important contribution for logistics and production engineers will be provided. Firstly, ad hoc decisions of logistics and production engineers for assigning parts to material flows can go hand in hand with a global analysis to get insight into the impact of these decisions. Secondly, rules of thumb can be developed based on part characteristics and these can help in developing a strategy for material supply. Summarized, the previously indispensable intuition of engineers - which always remained a source of subjectivity - will be replaced by an objective model. This outcome will also have an impact on reporting to higher management because decisions are more solidly grounded.

1.2.3 Content

The remainder of this dissertation is organized as follows. Chapter 2 presents the modeling approach. The two materials supply systems - line stocking and kitting - are accurately described and definitions are given. The flows of materials are investigated and cost functions are developed for the model. Finally, the mathematical model is presented.

Chapter 3 discusses the data gathering phase. It begins with the presentation of a case study. Next the structure of the data and the difficulties are discussed. In order to cope with missing data, an algorithm is developed for synthetic dataset creation. The algorithm is described.

Chapter 4 gives some preliminary results. Based on these results it is decided to extend the model to incorporate changing walking distances at the line and in the supermarket. The extended model is presented and the nonlinearities are discussed. In order to be able to easily solve the model, the objective function is linearized and a solution methodology is explained. General results for the extended model are compared with those of the preliminary model and it is shown that the new model better describes the real situation.

Chapter 5 gives computational results. A large number of tests were run on representative datasets to better understand the tradeoffs between the materials supply systems. First in Section 5.1, it is discussed how part and product mix characteristics have an influence on the decision to kit or supply in bulk. Next, in Section 5.2, the impact of materials supply parameters on the solution is studied.

Chapter 6 concludes the thesis and gives suggestions for future research.

2
Modeling Approach

In this chapter we present a mathematical model to study the trade-offs between kitting and line stocking, and the way part characteristics and plant design influence these trade-offs. The flow of parts, starting from the point of retrieval at the warehouse to the use point at the final assembly line, will be considered. In section 2.1 important concepts are defined. Section 2.2 discusses the material flows taking place for both of the material supply systems and the corresponding material handling costs. Section 2.3 presents the complete mathematical model. This chapter is an adaptation of Limère et al. (2011b).

2.1 Definitions

To be able to describe the two main methods of part supply consistently, strict definitions are given for some main concepts. We build upon the definitions given by Bozer and Mcginnis (1992).

A *part* is any component or subassembly which will be supplied to the line for assembly. For specific parts (such as mirrors, radio systems, ...) multiple variants exist, from which the customer can select one and only one.

A *part family* is the collection of all *variant parts* of a part, among which the customer must select his preferred one. Each of the parts in a part family can be selected for assembly, but two different parts of the same part family will never be assembled together in one end product. Variant parts from the same family are assumed to have identical weights and volumes. For the moment we dismiss optional parts since when not selected, often a placeholder part will have to be fitted. *Common parts* are parts that are the only element in their part family; no variants exist.

Kitting delivers specific sets of components and sub-assemblies to the shop floor in predetermined quantities, where each kit is collected, transported, and stored in a specific container. A *kit* is a specific set of components and sub-assemblies that together support one or more assembly operations for one given end product. There are two types of kits: stationary kits and traveling kits. A *stationary kit* is delivered to a workstation and remains there until it is depleted. A *traveling kit* moves along with the end product and feeds several workstations before it is depleted. Because each end product that comes off the assembly line is equipped with the particular models of the variant parts requested by the customer, each kit is different. Kits are therefore supplied to the line in sequence. Sequenced kits support the same assembly operations for consecutive vehicles, and therefore we say that they are of the same *kit type*. The content of a kit is constrained by a maximum weight and volume.

Kit assembly is the extra material handling operation where all the parts that are required for a particular kit are physically placed in the appropriate place in the kit container. The picking store where kitting operators walk to pick the needed parts is called a *supermarket*. Different design options exist for a kitting system (Brynzer and Johansson 1995). The kit assembly operation can be performed in a central picking store or in decentralized areas close to the assembly stations. It can be performed by assembly operators, or by special kitting operators. The parts that need to be kitted can be moved towards the operator (*part-to-picker*) or the operator can move to the picking locations (*picker-to-part*).

The *border of the line* (BoL) is the area parallel with the line where containers are stored. In order to capture important effects, but not overly complicate our model, we assume three types of containers: pallets, plastic boxes or totes, and kit containers. In the first place, pallets are wooden or plastic structures that carry stacked parts and are transported as unit-loads on forklift trucks. Secondly, plastic boxes or totes are smaller than pallets and are not transported as unit-loads but supplied through a *milk run* system. The milk run tour is carried out by a *tugger train* that consists of a motorized vehicle that pulls a number of un-powered trailers and that drives a route with multiple stops. Finally, *kit containers* carry several kits of the same *kit type*. We assume a kit container to be a rack with multiple levels, to store multiple kits in sequence. Similar to boxes, kit containers are supplied to the line through a *milk run* system. We assume all individual containers to be positioned along the line in the x-direction. This means no overlap along this direction is allowed and the assembly operator picks from a single facing. Additionally, boxes can be stacked vertically on racks (z-direction).

2.2 Material Flows and Corresponding Costs

This section zooms in on the two part feeding systems being studied and their respective costs. Section 2.2.1 and 2.2.2 give an accurate description of the material flows for respectively line stocking and kitted materials supply. Section 2.2.3 discusses the cost factors of interest.

2.2.1 Line Stocking

In line stocking, parts are supplied to the assembly workstations (WS) in packaging containers that contain multiple instances of the same part. In this research, we consider two kinds of packaging containers, namely pallets and boxes. For efficiency, parts are fed to the line in the original supplier packaging. Hence full containers are stored at the border of the line. When the packaging container is a unit-load (i.e., a pallet) only a single unit package can be handled at a time, and forklifts are used for internal transport to the line. Unit-loads will usually be stored as a single bin at the border of line and replenishment will be controlled by a reorder-point inventory system. When the original packaging is not a unit-load but a small box, internal transport is often provided by a tugger train that carries out a milk run tour periodically. Boxes will typically be stored two to a part at the border of the line and a two-bin inventory system controls the replenishment. Figure 2.1 represents the line stocking materials supply system. As can be noticed, boxes will, although they are stored two-bin, only occupy one facing at the line. Two identical boxes are positioned one behind the other on flow racks. Once the first box is empty, it will be removed and the second box will move forward. At the same time a signal is given to ask for replenishment.

2.2.2 Kitting

In this research, we will only study in-house kitting. Therefore, as with line stocking, parts are supplied to the factory in packaging containers - pallets or boxes - that contain multiple instances of the same part. In the factory an area is dedicated to carry out the kit assembly. We assume a central supermarket where kitting operators walk to pick the needed parts. In our model we consider stationary kits. We assume that the central picking supermarket is logically organized in picking zones, where an aisle represents a zone which contains all variant parts that can be consolidated in a kit for a certain work station. Furthermore we assume multiple kits of the same type are assembled in batches of five because five kits fit on one rack. The supermarket is replenished from the unit-load warehouse and box warehouse and stores pallets as well as boxes. This supermarket configuration has been observed in different vehicle manufacturing plants by the authors. The kit containers contain multiple kits of the same type, and are transported to the work stations and stored at the border of line. As one kit is consumed per takt time, kit container replenishments are needed according to constant time intervals. We assume the kit containers are delivered by a tugger and internal transport is carried out as a milk run tour.

Figure 2.2 illustrates the proposed kitting materials supply system.

2.2.3 Cost Factors

Different methods of line feeding have an impact on:

- Operator efficiency: Kits can be positioned right where the operator needs them whereas bulk containers are spread along the border of the line. Picking distances will therefore be larger in the case of line stocking. Moreover, the operator does not have to search for the proper parts when vehicle specific kits are provided. This increased productivity in case of kitting needs to be reflected in the cost calculations for picking at the workstations.

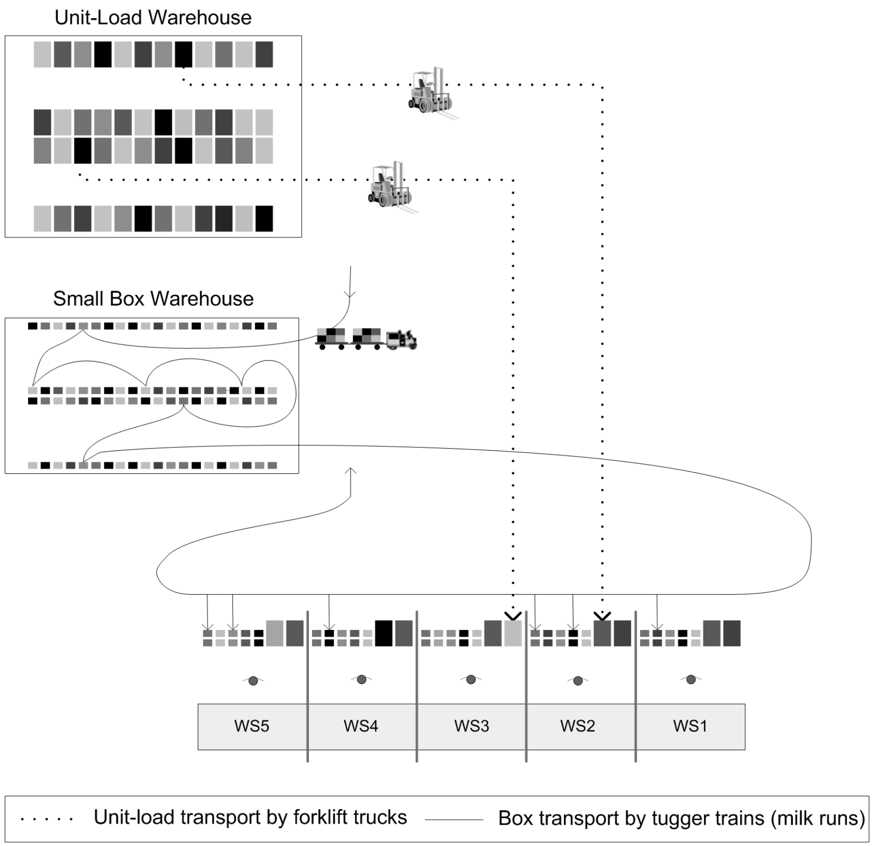


Figure 2.1: *Line stocking.*

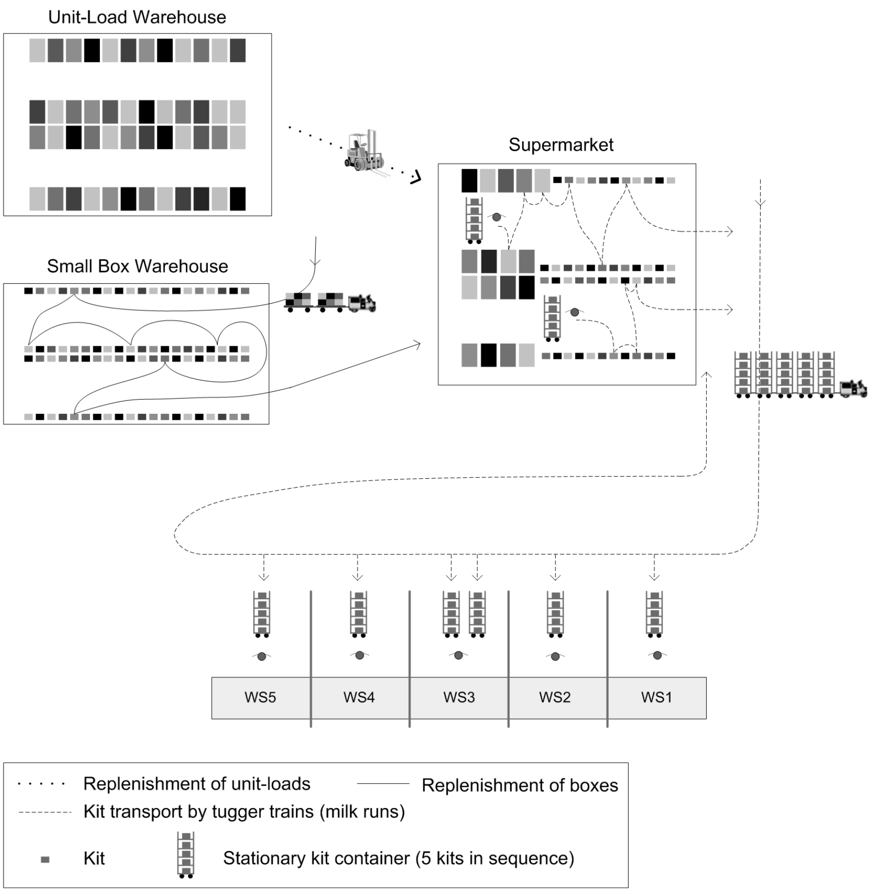


Figure 2.2: *Kitting.*

- Line space requirement: A limited number of kits requires less space at the line than a complete range of component containers.

- Material handling cost: The cost of supplying the parts from the warehouse to the line depends on the method of line feeding chosen. In the case of kitting, a supermarket has to be replenished as needed and kit assembly will consume additional time and effort. In the case of line stocking direct supply from the warehouse to the line takes place.

- Inventory cost: The more inventory can be kept at the supplier, the lower the internal inventory cost. However, since we only consider in-house kitting we assume no influence on inventory levels. When kitting, less inventory is stored at the line but overall we expect the same inventory within the factory walls.

- Quality: As already elaborated in the literature review, a line feeding method may also have an influence on end product quality and on production interruptions. However, as no experimental studies exist that discuss the impact on quality, the effect is currently left out of consideration.

2.3 Mathematical Model

A mixed integer programming model is developed to assign individual part families to the two materials supply system alternatives to minimize the total costs, given the average part and production mix characteristics. This is a static and deterministic optimization problem, where the costs are the average yearly labor costs for operator picking at the line, internal transport, the kit assembly operation and replenishment of the supermarket. Only operational running costs are taken into account. As no automation is considered, investment costs will be low compared to the cost of labor and are assumed to be negligible. The main decision for each part family is whether to kit or not. This decision is denoted by a binary decision variable x_{is} which is one if a part i should be supplied to workstation s in bulk and zero if it should be kitted. Additional decision variables determine the number of kits in the system. We will derive next detailed expressions for the various cost components of the system. We will start with the picking cost at the use-point at the assembly line, and will continue upstream with the internal transport cost, the cost for kitting, and finally the replenishment cost of the supermarket. In the remainder of the section, the cost of an operator hour is denoted as OC.

2.3.1 Picking at the Line

The labor cost for operator picking at the assembly line, is influenced by the materials supply method. On the one hand, the time to pick a unit of part i from a bulk container at station s, tp_{is}^{bulk}, is determined by the time the operator has to search for the required part in the bulk stock, τ^{bulk}, and the time to walk the distance to the container, Δ_{is}^{bulk}, back and forth at a walking velocity OV. It is defined by:

$$tp_{is}^{bulk} = 2\frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk} \tag{2.1}$$

On the other hand, the time to pick a unit from a kit, tp^k, is determined exclusively by a time to walk the distance to the kit container, Δ^k, back and forth. The searching time is eliminated as the required parts are unmistakably presented to the operator in a kit. tp^k is represented by:

$$tp^k = 2\frac{\Delta^k}{OV} \tag{2.2}$$

The labor cost for operator picking at the assembly line is then given by:

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[x_{is} tp_{is}^{bulk} + (1 - x_{is})\, tp^k \right] \tag{2.3}$$

Where q_{is} is the yearly usage of part i at station s.

2.3.2 Transport to the Line

The internal transportation cost to the workstations, C_{tpt}, consists of the cost of transportation of unit-loads, boxes and kits to the line. Loading at the warehouse or at the supermarket and unloading at the workstations also has to be included in the transportation costs. Yet, we will not model loading and unloading explicitly. Instead we will adjust the average velocities of material handling equipment to cover downtime due to loading and unloading.

Transportation of a unit-load is carried out as point-to-point transport by forklift trucks. The time to transport part i to workstation s is thus determined by the distance from the unit-load warehouse to work station s, D_s^p, back and forth, at a forklift truck velocity V^p, and by the number of unit-loads that need to be supplied to that station, i.e. the usage rate q_{is} divided by the packing quantity n_i. The cost for unit-load transport can then be defined by:

$$C_{tpt}^{pallet} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is} \left(2 \frac{D_s^p}{V^p} \frac{q_{is}}{n_i} \right) \tag{2.4}$$

Transport of boxes is organized as milk run tours. Batches of boxes of different part numbers are supplied to the correct work stations on tugger trains. The mixed load is collected at the warehouse and the tugger train passes by all work stations, dropping off the parts at the correct use points. The time for one milk run is defined by the distance of the milk run tour, D^b, divided by the velocity, V^b. Furthermore, the yearly number of tours to the line depends on the number of boxes that needs to be supplied to the station, i.e. q_{is}/n_i , on the capacity of the tugger train, A^b, and on the expected capacity utilization of the tugger train, ρ^b. The cost for box transportation can then be defined by:

$$C_{tpt}^{box} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_b} x_{is} \frac{\frac{D^b}{V^b} \frac{q_{is}}{n_i}}{A^b \rho^b} \tag{2.5}$$

Transport of kits is organized as milk run tours as well. Batches of kits are supplied to the correct work stations on tugger trains. A tugger pulls several kit types at once and drops the kit containers/racks off at the use points at the stations. The time for one milk run is defined by the distance of the milk run tour, D^k, divided by the velocity to transport kits, V^k. Furthermore, the yearly number of kits that need to be supplied to the station, is $K_s d$, where K_s is the number of kits needed at stations s to assemble one vehicle, and d is the yearly demand for vehicles. The yearly number of tours to the line then depends on $K_s d$, on the capacity of the tugger train, A^k, and on the expected tugger capacity utilization, ρ^k. The cost for kit transport finally is defined by:

$$C_{tpt}^{kit} = OC \sum_{s \in S} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k} \tag{2.6}$$

The total transport cost is the sum of the costs for the three separate transportation types.

$$C_{tpt} = C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{kit} \tag{2.7}$$

2.3.3 Kit Assembly

A third cost is the labor cost for the kit assembly operation, denoted by C_{kit}. The average time to pick a certain part i in the supermarket from its bulk container, tk_{is}, depends on the opportunity for picking multiple units of that part at once. We assume that multiple kits of the same type are assembled in batches. The opportunity for batch picking part i to assemble it in a kit for station s, θ_{is}, i.e. the number of units of part i that will on average be picked in one pick when the part is kitted, is then defined by:

$$\theta_{is} = \max\left\{ \min\left(\frac{q_{is}}{d} B^k, a_i\right), \frac{m_{is}}{\lceil m_{is}/a_i \rceil} \right\} \tag{2.8}$$

With,

q_{is}	Yearly usage of part i at station s
d	Yearly demand for end product (= vehicle)
B^k	Batch size for assembling kits
a_i	Maximum number of units of a part i in one pick due to physical characteristics (weight, volume) of part i
m_{is}	Number of units of part i assembled per vehicle (if the specific variant part i is used) at station s

We will give an example to understand the formula for θ_{is}. Consider six parts that need to be kitted. Table 2.1 gives a summary of the part characteristics and the calculated values for θ_{is}. The kit batch size B^k is assumed to be five kits. We notice that the average usage of all parts, q_{is}/d, is equal but m_{is} and a_i vary.

Table 2.1: *Example for the understanding of equation 2.8*

	part 1	**part 2**	**part 3**	**part 4**	**part 5**	**part 6**
m_{is}	1	5	1	5	1	5
q_{is}/d	50%	50%	50%	50%	50%	50%
a_i	1	1	3	3	5	5
θ_{is}	1	1	2.5	2.5	2.5	5

If we look at the resulting opportunity for batch picking we can see that as long as $a_i = 1$, this means that the physical part characteristics do not allow that the part is picked at more than one unit at a time, $\theta_{is} = \max\{1; 1\} = 1$.

When $a_i = 5$, a higher opportunity for batch picking exists. The real value for θ_{is} then depends on the one hand on the average usage of a part within a batch of kits, $(q_{is}/d)B^k$. This is the first term in the formula. But on the other hand also the spread of usage matters. Figure 2.3 gives examples for the real usage of a part with $m_{is} = 1$ and a part with $m_{is} = 5$. These examples are randomly drawn. We can see that the usage of a part with $m_{is} = 1$ is equally spread over time, but the usage of a part with $m_{is} = 5$ takes place in *lumps* of five units. This *lumping* induces a higher opportunity for batch picking, namely five parts will be picked at once. In the formula this is realized by the latter term, $m_{is}/\lceil m_{is}/a_i \rceil$, and $\theta_{is} = \max\{2.5; 5\} = 5$.

When $a_i = 3$, the physical characteristics of the part avoid that one can benefit from the demand in *lumps* and $\theta_{is} = 2.5$ in both cases ($m_{is} = 1$ and $m_{is} = 5$).

Obviously θ_{is} can never be less than 1, because none of the subterms can be less than 1.

The average time allocated to picking one unit from a bulk container of part i to kit for station s, tk_{is}, is then defined by the time the operator has to search for the required part in the supermarket stock, τ^k, the time to walk the distance to the container, Δ_{is}^k, back and forth at a walking velocity OV, and θ_{is}:

$$tk_{is} = \frac{\left({}^{2\Delta_{is}^k}/_{OV} \right) + \tau^k}{\theta_{is}} \tag{2.9}$$

Consequently, the labor cost for kit assembly is:

$$C_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} \left[\left(1 - x_{is}\right) q_{is} t k_{is} \right] \tag{2.10}$$

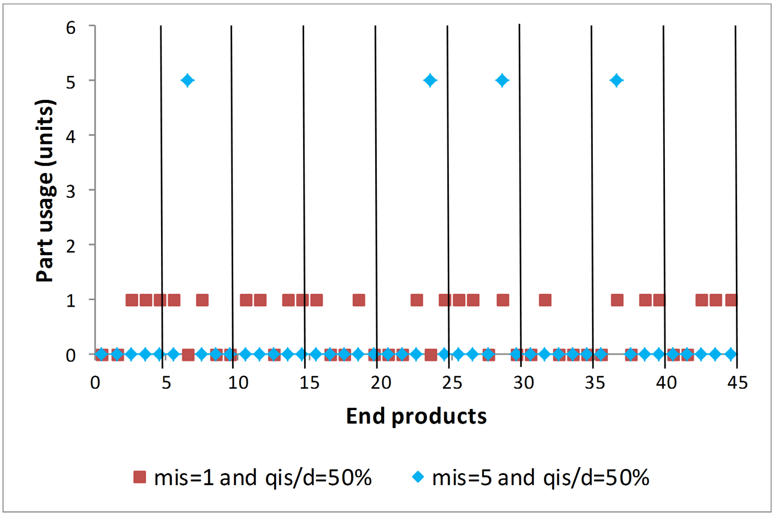


Figure 2.3: *Real usage of two parts with an equal average usage rate but a different m_{is}*

2.3.4 Replenishment of the Supermarket

Finally, the labor cost for the replenishment of the supermarket, C_{repl}, is determined by a constant cost for the replenishment of one box, R^b, and a constant cost for the replenishment of one pallet, R^p. The total replenishment costs can then be defined as:

$$C_{repl} = \sum_{s \in S} \sum_{i \in I_s \cap I_p} \left[\left(1 - x_{is}\right) \frac{q_{is}}{n_i} R^p \right] + \sum_{s \in S} \sum_{i \in I_s \cap I_b} \left[\left(1 - x_{is}\right) \frac{q_{is}}{n_i} R^b \right] \tag{2.11}$$

2.3.5 The Complete Model

The four sub-costs are described above. The complete model is now given next.

$$\min C_{total} = C_{pick} + C_{tpt} + C_{kit} + C_{repl} \tag{2.12}$$

Subject to,

$$K_s \geq \sum_{i \in I_s} \left[(1 - x_{is}) \left(\frac{m_{is} w_i}{|V_i|} \right) \Big/ w^k \right] \quad \forall s \in S \tag{2.13}$$

$$K_s \geq \sum_{i \in I_s} \left[(1 - x_{is}) \left(\frac{m_{is}/v_i}{|V_i|} \right) \right] \quad \forall s \in S \tag{2.14}$$

$$\sum_{i \in I_s \cap I_b} \left(\frac{x_{is}}{H^b} \right) \leq N_s^b \quad \forall s \in S \tag{2.15}$$

$$N_s^b L^b + \sum_{i \in I_s \cap I_p} x_{is} L^p + K_s L^k \leq L_s \quad \forall s \in S \tag{2.16}$$

$$x_{is} = x_{js} \quad \forall s \in S, \forall i \in I_s, \forall j \in V_i \tag{2.17}$$

With,

K_s	Integer auxiliary variable Number of kits needed at stations s to assemble one end product
N_s^b	Integer auxiliary variable Number of facings needed to store boxes along station s (with vertical stacking of boxes)
m_{is}	Number of units of part i assembled per vehicle at station s
w_i	Weight of part i
V_i	Set of variant parts of $i \in I$; the family of part i
w^k	Weight constraint on one kit unit; maximum weight per kit
v_i	Number of units of part i that a kit can maximally hold; this categorical parameter represents the volume (small, medium, large, extra large) of a part i {100, 20, 5, 1}
L^b	Length of a box along the line
H^b	Vertical stacking height of boxes (units) at the BoL
L^p	Length of a pallet along the line (we assume no stacking of pallets at the line)

L^k Length of a kit container/rack along the line (we assume no stacking of kits containers at the line)

L_s Available length along workstation s

Constraints (13) and (14) are respectively the weight and volume constraint for kits. More than one kit is needed at a station s ($K_s > 1$) if the total weight of all parts kitted at station s exceeds the limit w^k (13). More than one kit is needed at a station s ($K_s > 1$) if the total volume occupation (%) of all parts kitted at station s exceeds 100 percent (14). Division by the cardinality $|V_i|$ ensures that if a part family consists of multiple variant parts only one free space needs to be provided in the kit, as only one of the variant parts will be required per end product.

The reason why both a weight and a volume constraint for a kit is required, can be illustrated with a simple example. Assume a part supplied in a box for which $w_i = 2\,\text{kg}$ and $n_i = 2$. This means that the volume of the part is the constraining parameter. Otherwise, since a box can carry 50 kg, one would expect the box to be able to contain 25 units of the part instead of 2 units. If the kit is to be composed in a box of the same size and capacity, we would assume the same content to be able to fit in one kit ($v_i = 2$). However, if only a weight constraint of 50 kg was imposed one would mistakenly assume that, after including 2 units of the part, only $2 * 2\,\text{kg}/50\,\text{kg} = 8\%$ of the kit would be filled and the remaining 92% would be free for other parts. Nevertheless, in reality a considerable volume of the kit would be already occupied. Figure 2.4 gives a representation of such a part. As can be seen from the figure, no additional unit of the part can be fitted, but other smaller parts may be included in a kit.

Figure 2.4: *An example of a large volume/low weight part*

Equation (15) calculates the required length along work station s to store the boxes supplied in bulk at the border of line, given that they can be stacked vertically on flowracks. Constraint (16) represents the space constraint at the line. As already explained, we assume that picking at the line is done from one facing, i.e. the space constraint at the line is one-dimensional. The space required for boxes, pallets and kits is limited to L_s, the available length along workstation s.

Finally, constraint (17) ensures that if one part in a family is assigned to a certain supply system, all variant parts are assigned to the same system. This assumption is added due to practical implementation considerations. It would be too confusing for the operator if one variant of a part would be supplied in bulk and others would be kitted.

2.4 Conclusion

A mathematical optimization model is proposed that allows us to examine the relation between product and part characteristics and the optimal system of materials supply. This model offers the opportunity to select for each individual part the materials supply method which is most cost effective for the overall materials delivery system. Consequently, an objective justification can be given for the development of hybrid feeding policies where some parts are kitted and others are supplied in bulk.

Moreover, the model is linear which facilitates the solution method. It is implemented using the modeling language AMPL 11.2 and solved with CPLEX 11.2. Running times will be presented in Chapter 4, based on the datasets described in Chapter 3.

3
Data Gathering

To be able to extensively test the trade-offs between kitting and line stocking, data is required. As mentioned before, studying the supply of parts to the line is a rather unexplored field of research. Therefore, no data is available yet to study the problem thoroughly. Because of the numerous parameters that are needed as input, it is impossible to create a fictitious dataset that captures all the complexities of a real life situation.

This chapter reports on data requirements and on the data obtained from an industrial case study to satisfy these requirements. Moreover, to acquire a better understanding of the problem of materials supply, we want to apply the model to numerous datasets. Since no established test-bed is available for a comprehensive computational study, firstly representative datasets need to be developed. This chapter will also discuss the generation of synthetic datasets based on the characteristics of the original data obtained.

3.1 Case Company

The case company studied is a truck manufacturing company. The assembly line produces medium duty trucks in a one shift operation. A great variety of trucks is manufactured on this mixed-model assembly line. Many options can be chosen from and each truck is customized to the customer's wishes.

We will focus our attention on parts that are delivered from the supplier to the manufacturing plant in bulk. Parts that are currently supplied to the line in-sequence from suppliers are therefore out of scope of the study. Small parts that are supplied in small cardboard boxes are also left out of consideration because they are preferably not kitted. These parts are common parts like nuts and bolts, etc. and kitting them will not be beneficial. Often many units will be needed of these parts and counting the exact amount will be time consuming and error-prone. Furthermore, as the packages are very small these parts do not take a lot of space at the line. The remaining 1726 parts are delivered to the factory in two different packagings, i.e. boxes (plastic totes) or pallets. These are stored in automatic storage warehouses, i.e. a small box warehouse (SBW) for boxes and a high bay warehouse (HBW) for pallets. Currently these parts are supplied directly from the warehouse to the workstations, in their respective packaging. The purpose of the study is to investigate if some parts would be better grouped and supplied to the line into kits instead of in their individual containers.

3.2 Structure of the Data

We will now discuss in more detail the input that is needed for the model and the structure of the input parameters (Limère et al., 2011a). First of all general problem features need to be provided. These are related to:

- Plant layout
  - Distances from the warehouse to each of the work stations (D_s^p): these are needed to calculate the costs for fork lift transport of pallets.
  - Distances of the milk run tours by tuggers for the supply of boxes (D^b) and kits to the line (D^k).

  - The cost to replenish respectively one box (R^b) and one pallet (R^p) from the warehouse to the supermarket.

- Workstation layout
  - The average walking distance for an operator to pick from a kit (Δ^k).
  - The average walking distance for an operator to pick from bulk containers (Δ^{bulk}_{is}). This distance is larger than the distance to a kit.
  - The length of available storage area along a work station (L_s). We assume the border of line is organized in one facing along the direction of the moving assembly line (x-direction). Boxes are also stacked on racks vertically (z-direction).

- Supermarket layout
  - The average walking distance for an operator to pick from bulk containers (Δ^k_{is}).

- Operator productivity
  - The walking velocity of an operator (OV) (at the line or in the kitting area).
  - The average time to search for the required part from bulk stock at the line (τ^{bulk}) or in the kitting area (τ^k).
  - The hourly labor cost of an operator (OC).
  - The kit batch size (B^k): this is the number of kits that is assembled in a batch. If the same part number is required several times in the batch, the distance to the container of that part only has to be walked once by the operator.

- Material equipment capacity
  - Vehicle velocities for forklift trucks (V^p) and tugger trains (V^b en V^k).
  - The maximum number of units a tugger train can transport in one milk run (boxes (A^b) or kits (A^k)).
  - The expected capacity utilization of the tugger trains, given the variety in demands (ρ^b en ρ^k).

- Packaging dimensions

- The length of respectively a box (L^b), a pallet (L^p), and a kit container (L^k) along the line.
- The height (H^b) at which boxes are stacked at the border of the line (number of boxes).
- The maximum weight of a single kit (w^k).

Secondly, a dataset with parts that need to be supplied to the line and their respective characteristics is required. Every part will be defined by a record with the following fields:

- Part number: a unique key for each part (index i).
- Station: the work station to which the part needs to be supplied (index s).
- V_i: the part family to which part i belongs. A part family is a group of variant parts. Never more than one of the variant parts of the same family is assembled on an end product. Also note that parts of the same part family are always assigned to the same materials supply policy, i.e. they are either all bulk fed or either all kitted, because of practical implementation considerations.
- $|V_i|$: The cardinality of the part family to which part i belongs is also provided as a separate field.
- f_{is}: percentage of end products for which part i is assembled at station s (frequency).
- m_{is}: number of units of part i that will be assembled on an end product at station s (if that end product needs part i); this depends on the bill of material.
- q_{is}: yearly usage of part i at station s; this can be determined from f_{is}, m_{is} and the production d of the end product over the time horizon. $q_{is} = d \times f_{is} \times m_{is}$
- w_i: weight of part i
- $pack_i$: supplier packaging of part i {Box, Pallet}
- n_i: unit-load of part i in its supplier packaging (number of parts)
- v_i: volume measure for part i (number of units of part i that a kit can maximally hold)

- a_i: maximum number of units of a part in one pick due to physical characteristics (weight, volume) of part i

It is important to understand the structure of part data, especially with an eye on creation of new synthetic datasets. In the first place each part i is identified by a number of individual characteristic parameters. Certain relationships between the parameters need to be satisfied. For example, there is a link between the number of units of a part that fit into a certain packaging and the weight and the volume of the part. The weight and the volume of a part will also have an influence in the first place on the choice of packaging. Aside from individual part parameters, every part belongs to a part family V_i. The number of variant parts a customer can choose from is referred to as the cardinality of the part family $|V_i|$. For common parts, where the customer has no choice, the part family cardinality is one. Finally, parts are to be supplied to a certain work station s at the line. Figure 3.1 represents all the part parameters, and also shows connections between parameters that are related in some way. These relationships will further be illustrated by the case company data discussed in the next section.

3.3 Data Analysis

This section describes the data obtained from the case company. The order of the data presented will be the same as in section 3.2. Firstly, the general problem features are introduced. Figure 3.2 presents a simplified schematic plant layout. The layout shows the assembly line which exists out of three parallel line segments. Production takes place following a serpentine path over these three line segments. The high bay warehouse (HBW) is located to the right of the line and unit-load transport takes place using forklift trucks. The small box warehouse (SBW) is located in the lower right part of the plant. Transport of boxes to the line is carried out through a milk run system. The tour of the milk run is represented by a dashed line. The distances from the warehouse to each of the work stations (D_s^p) range from 54 to 302 m. The distance of the milk run tour for boxes (D^b) is 1640 m. At the moment there is no supermarket for kitting parts before delivery to the line. A supermarket area is proposed above the high bay warehouse. We assume a milk run tour for kits equally being 1640 m. The cost to replenish one box from SBW to the supermarket is estimated at €0.2 per box and the cost to replenish one pallet from HBW is

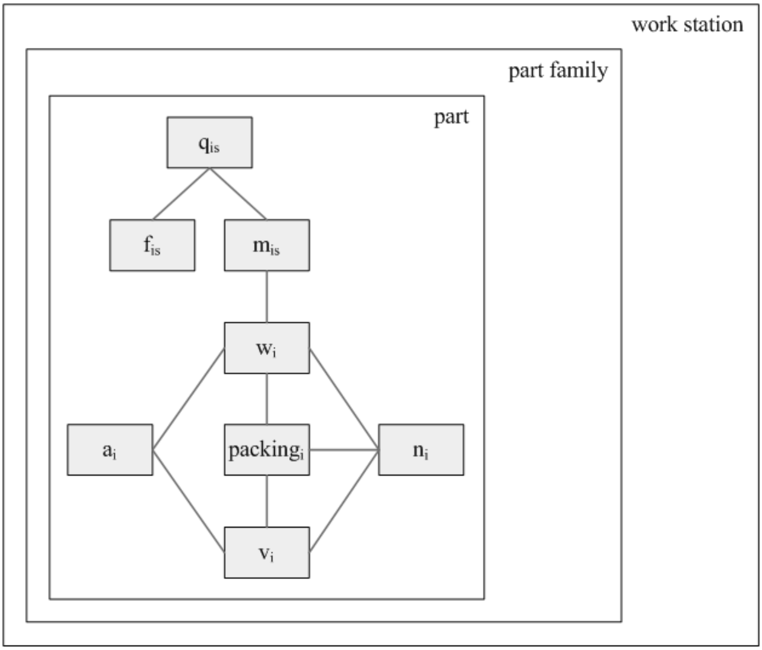


Figure 3.1: *Structure of the data*

estimated at €1.2 per box.

The workstations are 13 meters long. However, as we indicated when introducing the case company in section 3.1 we had to filter the database of parts. Supplier-sequenced parts are not taken into account and parts packaged in small cardboard boxes are also left out of consideration. Moreover parts that are too large to be kitted - be it in volume or in weight - are also ignored for analysis. This means these parts will have to be supplied to the line as they are supplied

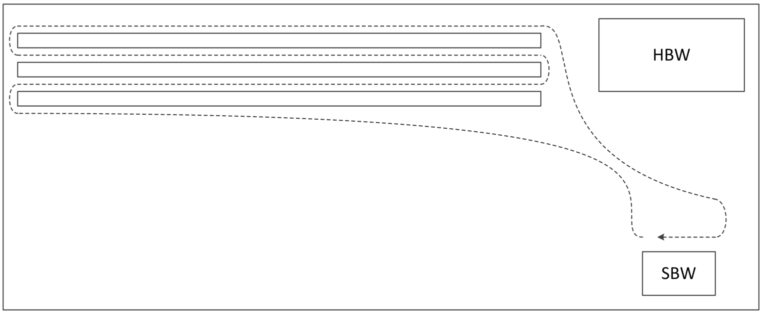


Figure 3.2: *Layout of the manufacturing plant*

originally and they will occupy part of the border of the line. For this reason we put the length of available storage area along a work station (L_s) at eight meter. The average walking distance to pick from bulk containers (Δ_{is}^{bulk}) is varied from two to three meters, depending on the usage rate of the part. This decision is based on an intelligent organization of stock at the line, for which high usage parts will be positioned closer to the operator and low usage parts further away. The average walking distance to pick from kit containers (Δ^k) is set at one meter and a half.

The operator walking velocity OV is fixed at 1 m/s (Meyers and Stewart, 2002) or 3600 m/h. The average time to search for the required part from bulk stock at the line and in the kitting area (τ^{bulk} and τ^k) is set at 1.08 s or 0.0003 h. The labor cost of an operator (OC) is 30 euro per hour. The kit batch size B^k can be chosen as desired and can vary between one and ten.

Concerning material handling equipment the model uses average velocities that include loading and unloading times. Thus, the velocity will be lower than the real velocity during transport. For forklift trucks a velocity of 2880 m/h (V^p) is used and for tugger trains doing the milk run tours a velocity of 2412 m/h (V^b and V^k). A tugger train will be able to transport 60 boxes per tour (A^b). However the milk run tours take place at constant time intervals and due to the variability in demand, only on peak moments the capacity will be fully utilized. On average the capacity utilization will only be 50% (ρ^b). For kits the capacity of the tugger train is 70 kits per tour (A^k) - i.e. 14 racks with 5 kits per rack - but the expected capacity utilization is higher, namely 80% (ρ^k) because transport needs can be predicted based on takt times, and transport can therefore be better controlled.

Finally the packaging dimensions at the case company are as follows: boxes and kits occupy 0.8 m (L^b and L^k) along the line whereas pallets occupy 1 m (L^p). Boxes are vertically stacked on racks on four levels high (H^b). The maximum weight of a kit is 50 kg.

Table 3.1 summarizes the case study features.

Next to the general case study features, the part specific parameters are studied. We obtained a total of 1726 parts to be supplied to 91 stations. This means, on average 19 different parts will be supplied to a station. However, if we look at the distribution of parts per station, we can see there exists a lot of variability. One station even needs up to 74 parts. Figure 3.3 represents the probability density plot of parts per station of the original database. We must reiterate that the orig-

Table 3.1: *Case study features*

Parameter	Value
OV (m/h)	3600
OC (€/h)	30
Δ_{is}^{bulk} (m)	
$q_{is} > 2500$	2
$2500 \geq q_{is} > 800$	2.5
$q_{is} \leq 800$	3
τ^{bulk} (h)	0.0003
Δ^{k} (m)	1.5
Δ_{is}^{k} (m)	
$q_{is} > 2500$	2
$2500 \geq q_{is} > 800$	2.5
$q_{is} \leq 800$	3
τ^{k} (h)	0.0003
B^{k} (number of kits)	5
D_{s}^{p} (m)	[54-302]
V^{p} (m/h)	2880
D^{b} (m)	1640
V^{b} (m/h)	2412
A^{b} (number of boxes)	60
ρ^{b}	0.5
D^{k} (m)	1640
V^{k} (m/h)	2412
A^{k} (number of kits)	70
ρ^{k}	0.8
R^{b} (€)	0.2
R^{p} (€)	1.2
w^{k} (kg)	50
L^{b} (m)	0.8
H^{b} (number of boxes)	4
L^{p} (m)	1
L^{k} (m)	0.8
L_{s} (m)	8

inal part database is filtered. Stations where only few parts are used according to the probability density plot are supplied with additional parts in supplier sequence and parts in small cardboard boxes.

For each of the parts q_{is} and m_{is} is given and the yearly production d is known to be 3500 trucks/year. Consequently f_{is} can be calculated for all parts. The yearly usage rates q_{is} vary from 175 units for slow movers to 89,250 for very popular parts. The probability distributions of m_{is} and f_{is} are presented in Figures 3.4 and 3.5.

The weight of one unit of a part is between five grams and 45.5 kilograms. Figure 3.6 displays the probability distribution of w_i.

With regard to the packaging type, 62% of the parts are supplied in boxes and the remaining 38% of the parts are supplied in pallets. As we discussed in section 3.2, not all part parameters are independent. Indeed, if we analyze the data, a relationship is discovered between the weight of a part and its packaging. Table 3.2 shows how the distribution box/pallet changes with the weight.

Moreover, another relationship exists between the weight of a part and m_{is}. Table 3.3 shows how m_{is} changes with the weight.

The unit-load of parts in their supplier packaging n_i is also given. This unit-load is related to the packaging type and the weight of a part. This relationship is demonstrated in Figure 3.7 where a number of probability distributions are presented. It can be seen that for increasing weights the histograms shift towards lower unit-loads. For pallets the unit-load values are more spread out than for boxes, which means that for parts in pallets volume will more often be a constraining factor.

In the original part dataset no volume measure v_i - number of units of part i that a kit can maximally hold - is given. Nevertheless, based on type of packaging and unit-load, a fictitious volume measure can be calculated. This volume measure will assure that a part always

Table 3.2: *Distribution of the packaging type in relation to part weight*

	P(box)	**P(pallet)**
$0 < w_i \leq 0.5\,\text{kg}$	94%	6%
$0.5\,\text{kg} < w_i \leq 1\,\text{kg}$	75%	25%
$1\,\text{kg} < w_i \leq 2\,\text{kg}$	48%	52%
$2\,\text{kg} < w_i \leq 5\,\text{kg}$	24%	76%
$5\,\text{kg} < w_i \leq 10\,\text{kg}$	2%	98%
$10\,\text{kg} < w_i$	0%	100%

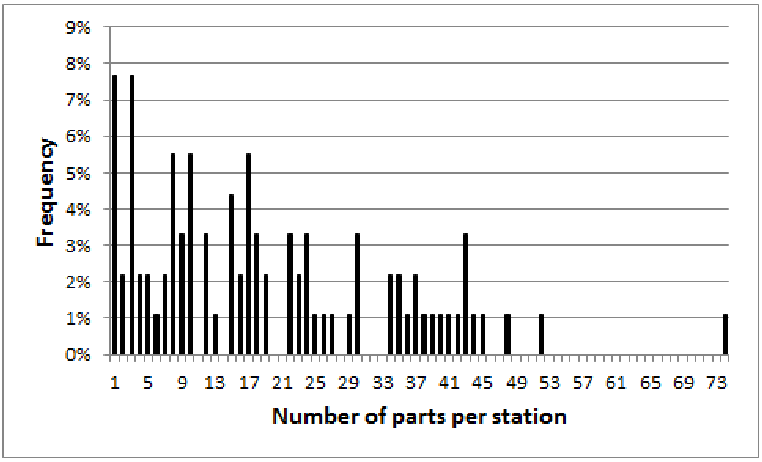


Figure 3.3: *Probability distribution of parts per station*

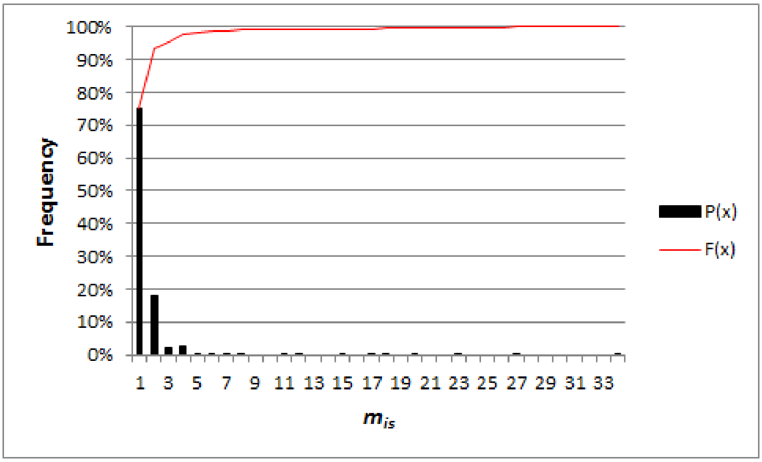


Figure 3.4: *Probability distribution of m_{is}*

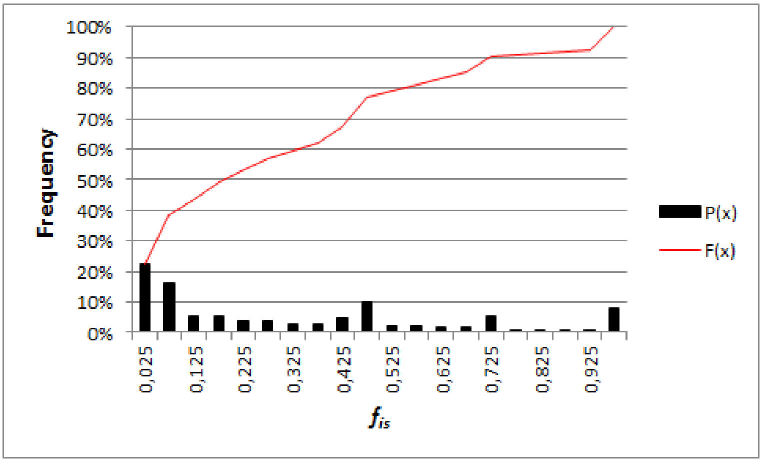


Figure 3.5: *Probability distribution of* f_{is}

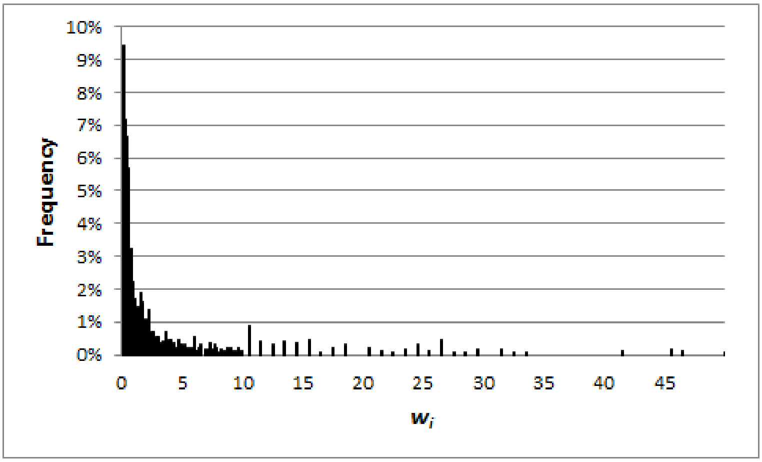


Figure 3.6: *Probability distribution of* w_i

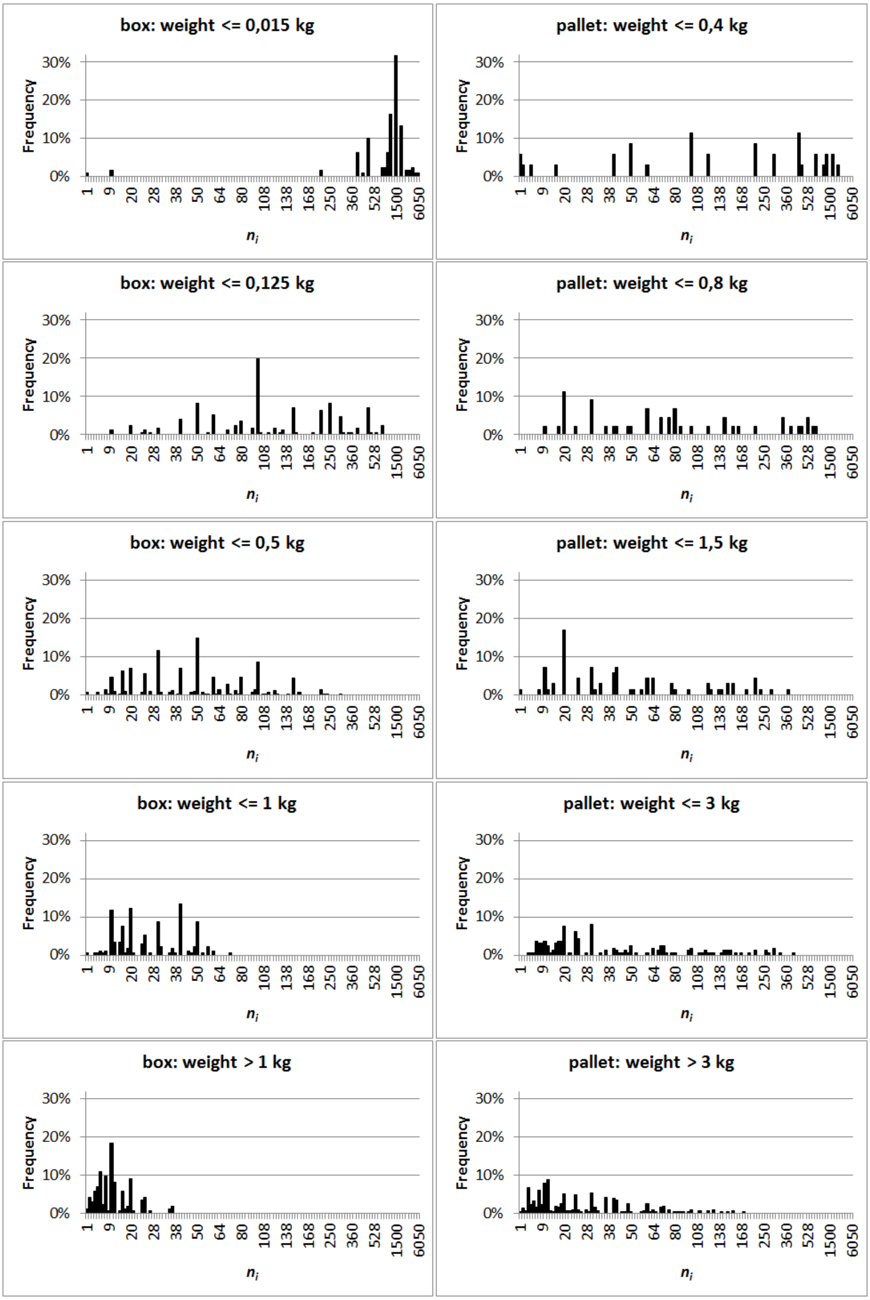


Figure 3.7: *Probability distribution of* n_i

Table 3.3: *Distribution of m_{is} in relation to part weight*

	$0 < w_i \leq 0.5\,\text{kg}$	$0.5\,\text{kg} < w_i \leq 5\,\text{kg}$	$5\,\text{kg} < w_i$
1	52,0%	74,7%	86,6%
2	14,0%	20,8%	12,2%
3	8,0%	0,4%	1,2%
4	8,0%	3,9%	0,0%
5	2,0%	0,0%	0,0%
6	2,0%	0,0%	0,0%
7	2,0%	0,0%	0,0%
8	2,0%	0,0%	0,0%
11	2,0%	0,0%	0,0%
18	2,0%	0,2%	0,0%
20	4,0%	0,0%	0,0%
34	2,0%	0,0%	0,0%

occupies at least the same volume in a kit as it occupies in its original supplier packaging. First of all, we assume the volume of one kit to be identical to the volume of one box and we assume the volume of one pallet to be sixteen times the volume of a kit or a box. By taking the reciprocal of the unit-load for boxes, $1/n_i$, and the reciprocal of sixteen times the unit-load for pallets, $1/(16 \cdot n_i)$, the percentage of volume occupation of a part in a kit is obtained. By once more taking the reciprocal of this percentage we obtain the theoretical number of parts that fit into one kit. If this number is smaller than or equal to 0.8, we will filter the part out the dataset as it is too large to fit into a kit. Then, if this number is larger then 0.8 but smaller than or equal to 1, we assume only one unit of the part fits in the kit ($v_i = 1$) and the kit is full when that part is kitted. Finally, if this number is larger than 1, we round it to the nearest integer. In case of a tie 'round half to even' is used as a tie breaking rule.

Values for a_i are calculated based on weight and volume of a part. The following conditions show how a_i is determined:

if $w_i < 0.1$ AND $v_i > 500$ **then**
  $a_i = 10$
else if $w_i < 0.2$ AND $v_i > 200$ **then**
  $a_i = 5$
else if $w_i < 1$ AND $v_i > 50$ **then**
  $a_i = 2$
else $a_i = 1$
end if

The only remaining parameters we have not discussed yet are V_i and $|V_i|$. These parameters are not available from the case company. Because of the importance of including $|V_i|$ in the model an estimate distribution is proposed based on our experience in industry (Figure 3.8).

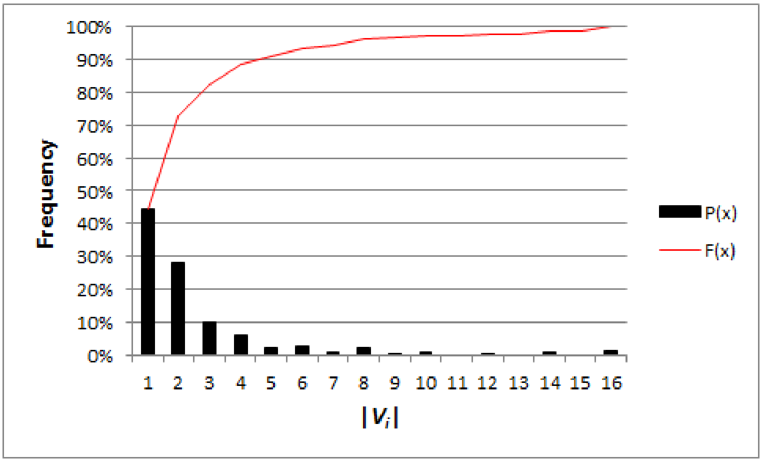


Figure 3.8: *Probability distribution of* $|V_i|$

3.4 Algorithm for the Creation of Synthetic Datasets

Because not all required data is available from the case company, i.e. no information is obtained about V_i and $|V_i|$, and because we want to apply the model to numerous datasets, an algorithm is developed for the creation of synthetic part datasets. This section presents the algorithm (Limère et al., 2011a).

The algorithm is coded in Visual Basic for Applications (VBA). Monte Carlo sampling from the characterizing distributions is supplemented with conditional statements to make sure the datasets are realistic as explained earlier in this chapter. Figure 3.9 describes the algorithm in pseudo-code.

Initially 2000 parts are created. In the first for-loop of the algorithm, a station cardinality is assigned to each part, through Monte Carlo sampling based on a random number from the distribution described in the previous section. Sequentially, station numbers are assigned to each part based on these cardinalities. For example if

Algorithm - Dataset creation

```
Create part numbers
for each part do
    Assign station number to part
    Assign part family cardinality and part family number to part
end for
for each family do
    Check if every part of the family is assigned to the same station
    if no then
        Adjust station assignment
    end if
end for
for each part assigned to a station do
    Assign a frequency f_is
end for
for each family do
    if only one part in the family (this is a common part) do
        while (f_is < 50% ) do
            Assign a new frequency f_is to the part
        end while
    else
        while (f_is > 100% ) and (number of iterations < 100) do
            Assign a new frequency f_is to all parts of the family
        end while
        if (f_is > 100%) do
            Assign a new (f_is = 1/|V_i| to all parts of the family
        end if
    end if
end for
for each part do
    Assign a weight w_i
    Assign a supplier packaging pack_i
end for
for each part assigned to a station do
    Assign m_is
end for
for each part do
    Assign a unit-load n_i
    Calculate a value for v_i based on n_i and pack_i
    Calculate a value for a_i based on w_i and v_i
end for
```

Figure 3.9: *Algorithm for dataset creation*

part one has a cardinality ten, the ten first parts are assigned to station one. The cardinalities originally assigned to parts two to ten are ignored. The second station then starts from part eleven and consists of a number of parts equal to the cardinality assigned to part eleven. The same procedure is used to assign parts to part families.

In the second for-loop of the algorithm, it is checked if the assignment of stations and part families is correct. Namely, parts of the same family should also be supplied to the same stations. The procedure followed before will not always assure that this is the case. Therefore a conditional if-statement is added, and if a part family is split over two stations, a corrective action is taken. The station assignment of the latter parts in the family is adjusted to match the station assignment of the first parts in the family. This modification will not have a considerable influence on the number of parts assigned to a station because parts are reassigned in two directions. Stations get more parts if a family is broken over the station and its successor, and less parts if a family is broken over the station and its predecessor.

In the third for-loop the parts are given frequencies, i.e. a percentage of end products for which the part is assembled. This is carried out by Monte Carlo sampling from the distribution proposed in the previous section.

In the fourth for-loop, the allocation of frequencies is checked. For part families greater than one part, the sum of the frequencies of all member parts should not exceed 100%. If the sum exceeds 100%, a new allocation of frequencies is carried out and the sum is checked again. This is carried out until the requirement is met or until 100 iterations are done. If by then no valid assignment is found, all parts in the family receive an equal part of a total frequency of 100%, i.e. f_{is} is exactly $1/|V_i|$. In order not to distort the original probability distribution of frequency too much, for common parts a minimum frequency of 50% is asserted. As long as this frequency is below this level, a new assignment is done.

In the fifth, sixth and seventh for-loops additional parameters are allocated to parts. Each time Monte Carlo sampling is used to make sure the parameters of the complete dataset correspond to the characterizing distributions from the case data. For $pack_i$ and m_{is} sampling is done from multiple distributions dependent on the weight of the part. For n_i multiple distributions are available and depending on the weight and the packaging of a part, sampling is done from the correct distribution. Finally, parameters v_i and a_i are calculated for all parts.

3.5 Conclusion

The algorithm written can be used to create a test-bed of instances to computationally test the model. General problem features can be adopted from the case study and part datasets are newly created. Moreover, input distributions now obtained from the case company can easily be changed to incorporate other parameter characteristics. Likewise, the general problem features can be changed. Possibilities are endless. In the future this algorithm will also be interesting in order to create test-beds for comparison of models and solution algorithms.

4

Extended Modeling Approach

4.1 Preliminary Results

The mathematical model presented in Chapter 2 is implemented using the modeling language AMPL 11.2, and solved with CPLEX 11.2 on an Intel Centrino Duo 1.67 GHz with 2 GB RAM memory. Table 4.1 presents the main results for a problem instance generated by the algorithm described in Chapter 3. The problem instance consists of 1773 parts to be supplied to 94 assembly line stations. The total cost of the optimal assignment given the existing space constraint is 371862 euros per year. In this optimal allocation 1027 parts will be supplied to the line in bulk and 746 parts, or 42% of the parts, will be supplied to the line in kits in sequence. These parts constitute a total of 50 kits delivered to 37 of the 94 stations.

We also calculated the total costs for the same problem instance if all items would be supplied to the line in bulk, and if all items would be kitted. Furthermore, if the problem instance is solved to optimality without space constraints, all parts will be assigned to bulk feeding (line stocking). CPU times for all problems are smaller than one

Table 4.1: Main results of the case study

	Total Cost (€/year)	# of parts kitted	# of kits	CPU time (s)
With space constraint				
Optimum	371 862	746 (42%)	50	0.999
Without space constraint				
Optimum	325 834	0 (0%)	0	0.609
All bulk	325 834	0 (0%)	0	0.031
All kitting	600 688	1773 (100%)	253	0.047

second.

We notice that the ‘all bulk’-scenario with 325834 euros per year is cheaper than the optimum with space constraint. The reason for a higher cost optimum is the available space at the border of the line, which is constrained to eight meter per station. The ‘all bulk’-scenario is therefore in reality not a feasible solution. In contrast, the ’all kit’-scenario with 600688 euros per year is much more expensive than the optimum. Although 42% of the parts are kitted in the optimal case, the 50 kits only constitute 20% of the kits in the ‘all kit’-scenario and the total cost does not increase proportionally with the number of parts kitted.

Figure 4.1 shows the detail of the costs. The ‘all-kit’-scenario leads to increased internal transportation costs. Kits are composed per station and it is not ensured that this composition will be dense. Even with the expected filling degree of milk run tours for kits being higher, transportation will be less efficient. Meanwhile, the line picking costs have decreased. However, additional material handling operations are required for the kit assembly and the replenishment of the supermarket, through which the decrease in line picking costs is offset. Looking at the optimal costs, given a space constraint, it can be seen that the change in costs with regard to the unconstrained ‘all bulk’-scenario is limited. Kits will be composed in such a way that transport efficiency is not significantly reduced and additional material handling costs are limited.

Figure 4.2 shows the space that is used along the border of the line (BoL) of each of the stations. For the ‘all bulk’-scenario this amounts to 25.6 meters per station. For the optimal assignment, the space along the border is limited to 8 meters per station. For stations where the space constraint can be satisfied by supplying everything in bulk, no changes are made. For the other stations, parts are kitted until the space needed at the border of line goes below eight meters.

If at this time the kits are not full, additional parts for which the total cost will decrease can be fitted. These parts will be ‘free riders’ because the transportation cost for the kit is already charged to the solution and does not need to be increased anymore. Because of kitting of ‘free riders’, the occupied space at the border of the line in the optimal assignment policy is not only reduced to eight meters, but even further. In Figure 4.2 it can be seen that there is much ’free riding’ when the space used at the border of line goes from above eight meters in the ’all bulk’-scenario to way below eight meters in the optimal assignment policy.

Noticing the lower cost for the ‘all bulk’-scenario, but realizing at the same time the infeasibility of this solution because of the space constraint, we were interested in seeing the evolution of the costs in the optimum when the percentage of kitting is fixed and evolves from zero to 100% of kitting. Figure 4.3 illustrates what happens. When more kitting is imposed, at first a roughly linear increase in costs can be observed. However, when the percentage of kitting amounts to around 50% and higher, the increase in total costs gradually turns into a steeper trend. A linear increase in the percentage of kitting then leads to a more than linear increase in total costs. With regard to the space constraint, Figure 4.4 demonstrates what happens to the space needed to store all parts at the border of the line. We can see that as more kitting is imposed, less space is needed at the border of the line. We emphasize here that the graph shows the *required* space for line stock instead of the *real* station length. In practice, this station length will be determined partly based on the required space for line stock, but also on the assembly times and assembly line speed.

Zooming in on the costs gives us more insight on where the sudden increase in costs above 50% of kitting comes from. Figure 4.5 presents the evolution of the subdivisions of costs while the percentage of kitting changes. One can see that where picking at the line and transport to the line each represent half of the costs in the case of bulk supply, in the case of 100% kitting the cost mainly consists of transport costs and kitting costs. The cost for picking at the line is halved and replenishment costs are inferior.

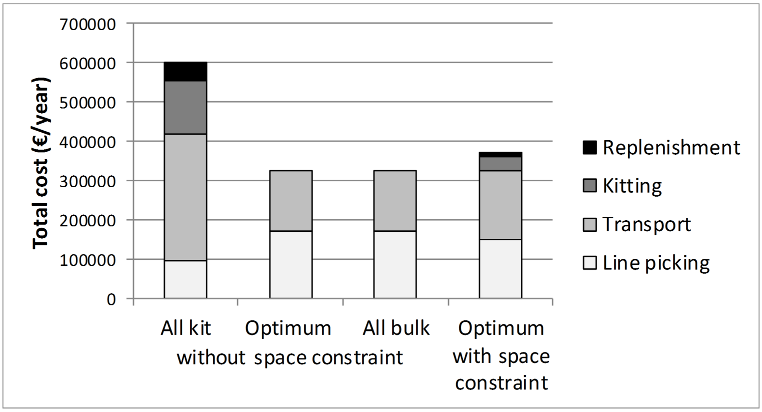


Figure 4.1: *Detail of the cost subdivision*

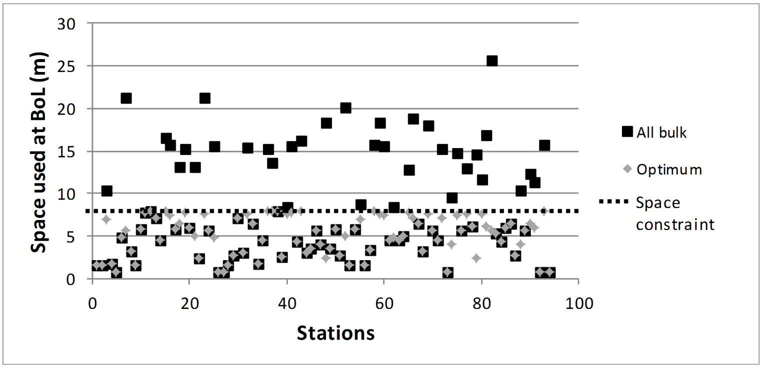


Figure 4.2: *Length used at the border of line of the stations*

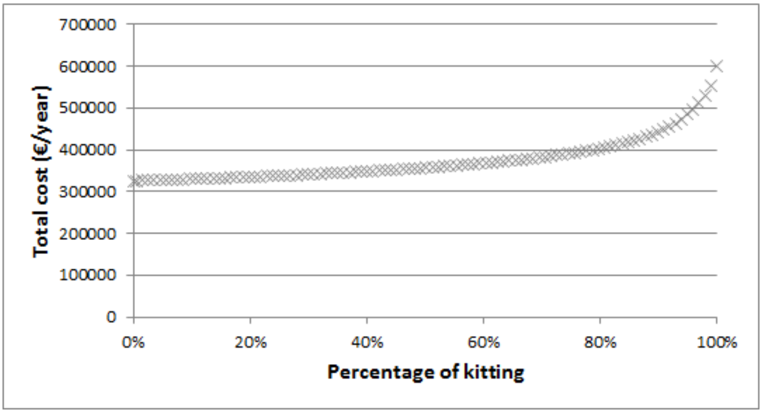


Figure 4.3: *Total costs as the percentage of kitting changes*

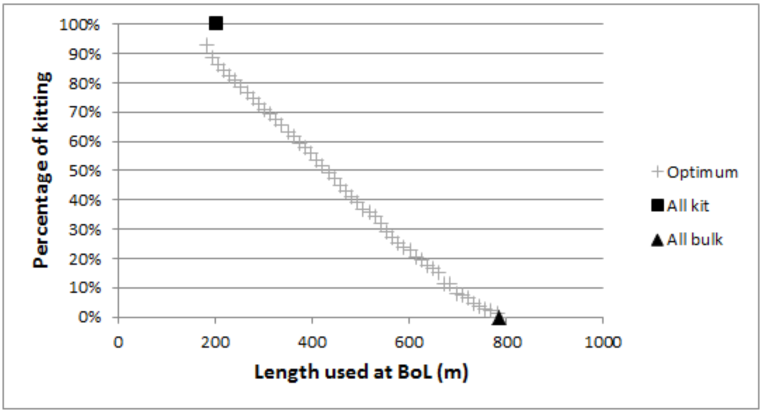


Figure 4.4: *Length used along the line as the percentage of kitting changes*

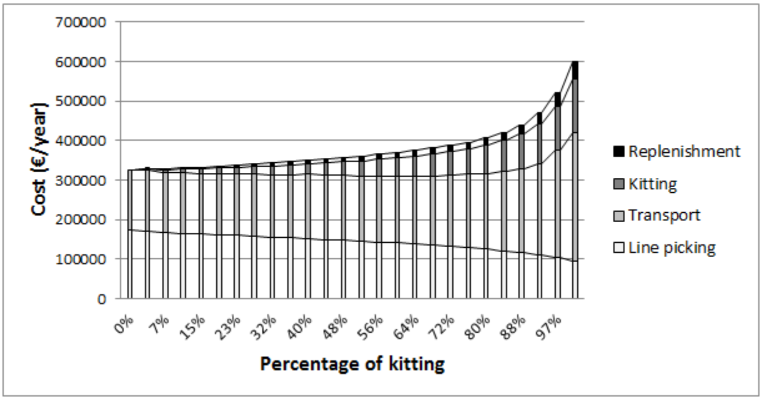


Figure 4.5: *Detail of the cost subdivision as the percentage of kitting changes*

4.2 Improved Picking and Kitting Cost Approximation

In general, regardless of the solution, we notice that around half of the costs are incurred in picking at the line and kit assembly. Because of the major influence of these activities on total costs, and because at the moment these activities are only roughly modeled - approximate average distances are used to model picking and kitting - we have decided to take a closer look and approximate them more accurately.

4.2.1 Picking Cost

In the first place we will zoom into the process of picking parts from bulk containers at the border of the line. In the base model the picking cost is calculated according to:

$$tp_{is}^{bulk} = 2\frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk} \tag{4.1}$$

In this equation Δ_{is}^{bulk} is the average distance to a bulk container at the line. This distance thus does not take into account the real organization of the border of the line, but approximates the real walking distances by an average. In the case study in Chapter 3 this average distance is diversified in multiple categories. The average walking distance to pick from bulk containers (Δ_{is}^{bulk}) is varied from two to three meter, depending on the usage rate of the part. This decision is based on an intelligent organization of stock at the line, for which high usage parts will be positioned closer to the operator and low usage parts further away. Although the formulation takes into account an intelligent organization of the line stock, it does not take into account that walking distances will be longer when a large stock is available at the line, and shorter when line stock is limited.

To approximate the walking distance to pick from bulk containers more accurately, the available stock at the line is taken into account. Figure 4.6 gives a representation of a border of line which is fully occupied and the walking distances we accordingly assume in the formulation. The depth of the line - i.e. the perpendicular distance between the operator working at the product and the border of line - is assumed to be 1.5 m. The average walking distance along the line is assumed to be 2 m. This distance comes from the assumption that the operator is working in the middle of the line. Sometimes he will have to walk half of the work station length which is 4 m, and sometimes he can pick parts immediately without having to move left or right. Thus on average he has to walk one fourth of the work station length.

If the border of line is not fully occupied with stock, this will have an influence on the required walking distance. Figure 4.7 shows that it makes no sense to spread all stock over the complete border of line (left), but stock will be centered around the use point at the line (right). The walking distance then still consists of walking the depth of the station, but additionally on average only one fourth of the width of the stock has to be walked, instead of one fourth of the complete station length.

The width of the stock can be calculated as a sum of the length along the line occupied by boxes, $N_s^b L^b$, the length occupied by pallets, $\sum_{i \in I_s \cap I_p} x_{is} L^p$, and the length occupied by kits, $K_s L^k$. Thus, Δ_{is}^{bulk} can be calculated as follows:

$$\Delta_{is}^{bulk} = depth + \frac{N_s^b L^b + \sum_{i \in I_s \cap I_p} x_{is} L^p + K_s L^k}{4} \tag{4.2}$$

Some remarks need to be made concerning this new formulation. Although by changing the formula we attempt to model the distance more accurately, we still approach the line feeding problem in a tactical way. This means we do not want to zoom in on the true organization of the line and therefore we still work with one average distance instead of real distances. Firstly, in the logic explained above we assume that the operator is working on the product in the middle of the work station and stock is centered around this use point. In reality in the automotive industry we often see continuously moving assembly lines. Because of the steadily moving conveyor belt the operator will not move the same distance towards the stock and back but he will

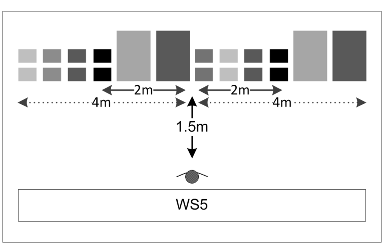


Figure 4.6: *Average walking distance from bulk containers - fully occupied BoL*

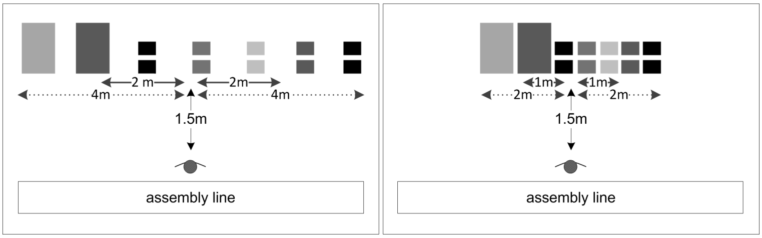


Figure 4.7: *Average walking distance from bulk containers - partly occupied BoL*

walk in a triangular manner. Moreover, the operator does not always work in the middle of the station but use points can be spread all over the station. Furthermore the distance is now calculated as a *Manhattan distance*. This means that we pretend the operator will only walk perpendicular to the line and along the border of line. In reality however the operator will cut off the corners and go straight to the container. This can easily be calculated by applying the *Phytagorean Theorem* but this would turn the distance measure in a non-linear measure. In the remainder of this chapter it will become clear why this is not desirable. To reduce the overestimation by the *Manhattan distance*, the parameter *depth* might be taken somewhat smaller than the real line depth.

Thus, it should be kept in mind that we still use an approximate measure. The main advantage of this formulation over the former is that it takes into account that kitting does not only shorten the picking distance for the parts in the kit, but it also shortens the picking distance from the remaining bulk containers as the line stock diminishes. Consequently, the model takes into the consideration that the solution itself - i.e. the assignment of parts to the preferred line feeding method - has an influence on the walking distances, which in turn may again have an impact on the solution. This obviously makes the assignment model non-linear, but later in this chapter we will explain how to deal with this.

The process of picking parts from kit containers at the border of the line is straightforward and was modeled as a fixed walking distance. There is no need to change this formulation. Therefore, in the base model and in the new model as well the picking distance is $\Delta^k = 1.5$.

For the final cost calculation of picking at the assembly line nothing changes. The cost is still given by:

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[x_{is} tp_{is}^{bulk} + (1 - x_{is})\, tp^k \right] \tag{4.3}$$

The products $(x_{is} tp_{is}^{bulk})$, which are products of two variables, turn the formulation into a non-linear mathematical model.

4.2.2 Kitting Cost

A second process we want to inspect so as to refine the cost formulation is the kit assembly process. Figure 4.8 shows us a representation of a commonly observed supermarket layout.

It is assumed that empty kit containers/racks are provided at one side of the supermarket and full kit containers/racks are picked up at the other side of the supermarket. This ensures that there is a smooth flow and kit operators are not crossing and hindering each other. It is also assumed that an operator will find all variant parts that can be consolidated in a kit for a certain work station are stored in one and the same aisle. Consequently, there is a fixed production time for each kit, that is the time to walk through one aisle without picking anything. This time is represented by FT^k. The total number of kits that need to be supplied to the line per year is $\sum_{s \in S} K_s d$. Hence, the fixed cost for all kits, FC_{kit}, is calculated by equation 4.4:

$$FC_{kit} = OC \cdot FT^k \sum_{s \in S} K_s d \tag{4.4}$$

Besides the above mentioned fixed cost, a variable kitting cost is also incurred for every part that needs to be kitted. The distance the operator needs to walk to pick each part is half the width of an aisle in the supermarket, $\Delta_{is}^k = aisle\_width/2$. The formula for the average operator time to pick a unit from a bulk container of part i to kit for station s, tk_{is}, remains the same as explained in equation 2.9.

The variable cost for all kits, VC_{kit}, is then calculated in equation 4.5:

$$VC_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} \left[(1 - x_{is})\, q_{is} tk_{is} \right] \tag{4.5}$$

The complete labor cost for kit assembly is:

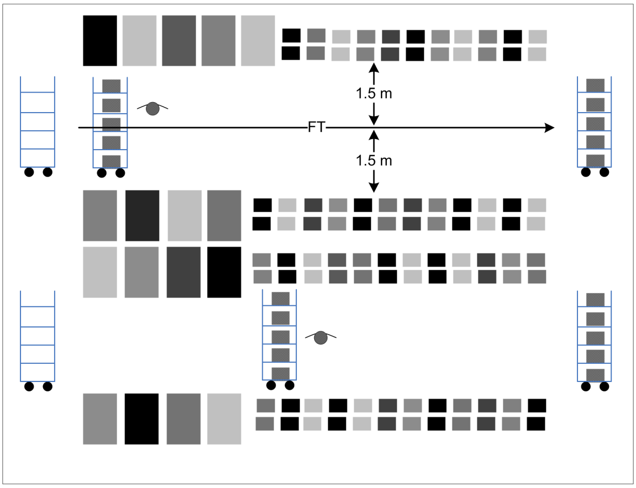


Figure 4.8: *Average walking distance to pick a part in the supermarket*

$$C_{kit} = FC_{kit} + VC_{kit} \tag{4.6}$$

Contrary to the picking cost, in this formulation no non-linear functions are introduced.

4.3 Solution Methodology

The new picking cost has turned the model into a non-linear mixed integer programming model. As CPLEX is a solver for linear and quadratic problems, it is not able to solve the model in its current form. When running the model an error message 'QP Hessian is not positive semi-definite' confirms that CPLEX cannot solve this non-convex problem.

A straightforward solution to this problem could be to switch to a non-linear solver. However, computationally linear problems are preferred over non-linear problems. In this section we will describe how our model is rewritten according to a formulation introduced by Glover (1975) and Torres (1991). The transformed model is a linear model which again can be easily solved by CPLEX.

In our model the non-linear terms are in the cost of picking from bulk containers:

$$\sum_{s\in S}\sum_{i\in I_s} OCq_{is}x_{is}\left(2\frac{\Delta_{is}^{bulk}}{OV}+\tau^{bulk}\right) \tag{4.7}$$

with,

$$\Delta_{is}^{bulk} = depth + \frac{N_s^b L^b + \sum_{i\in I_s\cap I_p} x_{is}L^p + K_s L^k}{4} \tag{4.8}$$

The binary variable x_{is} is multiplied with a function of multiple variables, i.e. Δ_{is}^{bulk} is a function of N_s^b, x_{is}, and K_s.

Torres (1991) explains how products of a binary variable and a function of continuous variables can be replaced by a new continuous variable if some specific constraints are added. This transformation is based on the technique introduced by Glover for bilinear products. The transformation is presented next for a mixed integer product $yF(x)$ ($y \in \{0,1\}$, $x \in \mathbb{R}^n$).

The mixed product $yF(x)$ may be replaced by a new continuous variable $p \in \mathbb{R}$ adding the constraints:

$$p \geq F(x) - U(1-y) \tag{4.9}$$

$$p \geq Ly \tag{4.10}$$

$$p \leq F(x) - L(1-y) \tag{4.11}$$

$$p \leq Uy \tag{4.12}$$

where $L < F(x)$ and $U > F(x)$ for all feasible $x \in \mathbb{R}^n$.

Because the mixed integer products in our model appear in the objective function and we deal with a minimization problem, constraints 4.11 and 4.12 may even be discarded as they will be satisfied automatically (Torres, 1991). For our problem the reformulation is the following:

$$\sum_{s\in S}\sum_{i\in I_s} OCq_{is}\left(2\frac{p_{is}}{OV}+x_{is}\tau^{bulk}\right) \tag{4.13}$$

with the following additional constraints,

$$p_{is} \geq \Delta_{is}^{bulk} - \left[\left(depth + \frac{L_s}{4} + \epsilon\right)(1 - x_{is})\right] \quad \forall s \in S, \forall i \in I_s \quad (4.14)$$

$$p_{is} \geq 0 \quad \forall s \in S, \forall i \in I_s \quad (4.15)$$

with ϵ any small number,

and where $0 < \Delta_{is}^{bulk}$ and $\left(depth + \frac{L_s}{4} + \epsilon\right) > \Delta_{is}^{bulk}$ for all feasible (i, s).

The complete model is now given next.

$$\min C_{total} = C_{pick} + C_{tpt} + C_{kit} + C_{repl} \quad (4.16)$$

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left(x_{is}\tau^{bulk} + 2\frac{p_{is}}{OV} + (1 - x_{is})\, 2\frac{\Delta_k}{OV}\right) \quad (4.17)$$

$$C_{tpt} = C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{kit} \quad (4.18)$$

$$C_{tpt}^{pallet} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is} \left(2\frac{D_s^p}{V^p}\frac{q_{is}}{n_i}\right) \quad (4.19)$$

$$C_{tpt}^{box} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_b} x_{is} \frac{\frac{D^b}{V^b}\frac{q_{is}}{n_i}}{A^b \rho^b} \quad (4.20)$$

$$C_{tpt}^{kit} = OC \sum_{s \in S} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k} \quad (4.21)$$

$$C_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} \left[(1 - x_{is})\, q_{is} \frac{\left(2\Delta_{is}^k / OV\right) + \tau^k}{\theta_{is}}\right] \quad (4.22)$$

$$C_{repl} = \sum_{s \in S} \sum_{i \in I_s \cap I_p} \left[(1 - x_{is}) \frac{q_{is}}{n_i} R^p \right] + \sum_{s \in S} \sum_{i \in I_s \cap I_b} \left[(1 - x_{is}) \frac{q_{is}}{n_i} R^b \right] \tag{4.23}$$

Subject to,

$$K_s \geq \sum_{i \in I_s} \left[(1 - x_{is}) \left(\frac{m_{is} w_i}{|V_i|} \right) \Big/ w^k \right] \qquad \forall s \in S \tag{4.24}$$

$$K_s \geq \sum_{i \in I_s} \left[(1 - x_{is}) \left(\frac{m_{is}/v_i}{|V_i|} \right) \right] \qquad \forall s \in S \tag{4.25}$$

$$\sum_{i \in I_s \cap I_b} \left(\frac{x_{is}}{H^b} \right) \leq N_s^b \qquad \forall s \in S \tag{4.26}$$

$$N_s^b L^b + \sum_{i \in I_s \cap I_p} x_{is} L^p + K_s L^k \leq L_s \qquad \forall s \in S \tag{4.27}$$

$$\Delta_{is}^{bulk} \geq depth + \frac{N_s^b L^b + \sum_{i \in I_s \cap I_p} x_{is} L^p + K_s L^k}{4} \qquad \forall j \in S, \forall i \in I_s \tag{4.28}$$

$$\Delta_{is}^{bulk} - \left[\left(depth + \frac{L_s}{4} + \epsilon \right) (1 - x_{is}) \right] \leq p_{is} \qquad \forall j \in S, \forall i \in I_s \tag{4.29}$$

$$p_{is} \geq 0 \qquad \forall j \in S, \forall i \in I_s \tag{4.30}$$

4.4 Comparison with the Base Model

The extended model is now compared to the base model and results are evaluated. First of all Table 4.2 gives the additional input for the extended model. To reduce the overestimation by the *Manhattan distance* as explained previously, *depth* is put at 1 m even though the real depth of the station is 1.5 m. FT^k is estimated at 10 seconds or 0.00278 h, and the distance Δ_{is}^k that the kitting operator has to walk to each part is 1.5 m.

We have applied the extended model to the same dataset as the base model. Table 4.3 presents the results.

The first thing that needs to be mentioned is that the running

Table 4.2: *Data input - Extended model*

Parameter	**Value**
depth (m)	1
FT^k (h)	0.00278
Δ_{is}^k (m)	1.5

Table 4.3: *Main results of the case study - Extended model*

	Total Cost (€/year)	**# of parts kitted**	**# of kits**	**CPU time (s)**
With space constraint				
Optimum	382 271	987 (56%)	55	4.809
Without space constraint				
Optimum	367 423	645 (36%)	31	5.356
All bulk	427 364	0 (0%)	0	0.110
All kitting	639 835	1773 (100%)	253	0.375

times are higher than for the base model. This was expected because new continuous variables and constraints are added. Table 4.4 gives an overview of the variables and constraints for the optimization model with space constraints. Despite the increase in complexity and consequently in running times, there is no problem at all. CPU times are still in the order of seconds and since our problem is at a tactical level, this is still more than fast enough.

Secondly we notice that all costs are higher for the extended model. To understand where this difference comes from, we first take a look at the bar chart presented in Figure 4.9.

The cases that can most easily be compared are the case where all parts are kitted and the case where all parts are supplied to the line in bulk. For these cases we know that the solution for the base model and the extended model is identical, but still there is a difference in costs. For the case where all parts are kitted Figure 4.9 shows that the difference is completely caused by a higher kitting cost. In Figure

Table 4.4: *Number of variables and constraints - Base model versus extended model*

	Base model	Extended model
binary variables	1773	1773
integer variables	188	188
continuous variables	0	3640
constraints	8416	12037

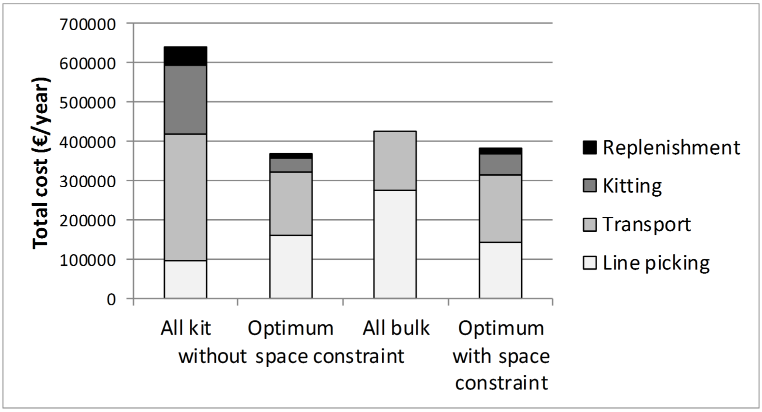


Figure 4.9: *Detail of the cost subdivision - Extended model*

4.10 the cost per kit for all workstations is depicted. It is clear that the average cost per kit is higher for the new model. With €0.20 per kit, it is 24% higher that the average cost per kit for the base model.

For the case where all parts are supplied to the line in bulk Figure 4.9 shows that the increase in total costs is completely caused by a higher line picking cost. To track this cost increase Figure 4.11 shows the value for Δ_{is}^{bulk} for all parts. For the base model these distances are independent of the solution and vary between two and three meters. For the extended model though the distances are dependent of the solution. For the all bulk solution we see that the operator walking distances are a lot higher on average (3.9 m) than the fixed distances imposed in the base model (2.67 m). This explains therefore the higher cost of the 'all bulk'-scenario when the extended model is used. The operator walking distances are also shown for the optimal case with space constraint. This data series has less data points then the two other series because we only have a value for Δ_{is}^{bulk} for the parts that are assigned to bulk as a line feeding method. Instead, the average operator walking distance here (2.21 m) is lower than the average of the fixed distances imposed in the base model (2.67 m). The new operator walking distances much better represent the situation seen in industry. If all parts are brought to the line in bulk, stations are often overloaded and walking distances indeed become very large. In the optimal situation where 56% of the parts are kitted, not only the distances for the operator from these parts in kits is smaller, but also the parts that remain in bulk can be put closer.

Contrary to the 'all bulk'- and the 'all kit'-solution, the optimal cases for both models - with and without space constraint - are some-

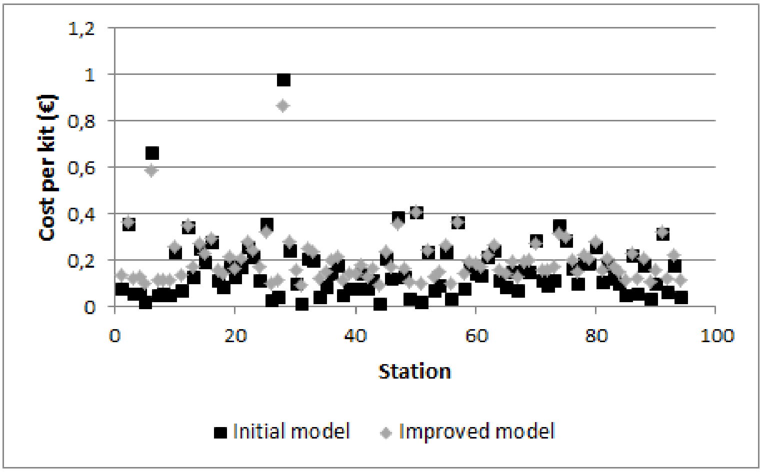


Figure 4.10: Comparison of cost per kit

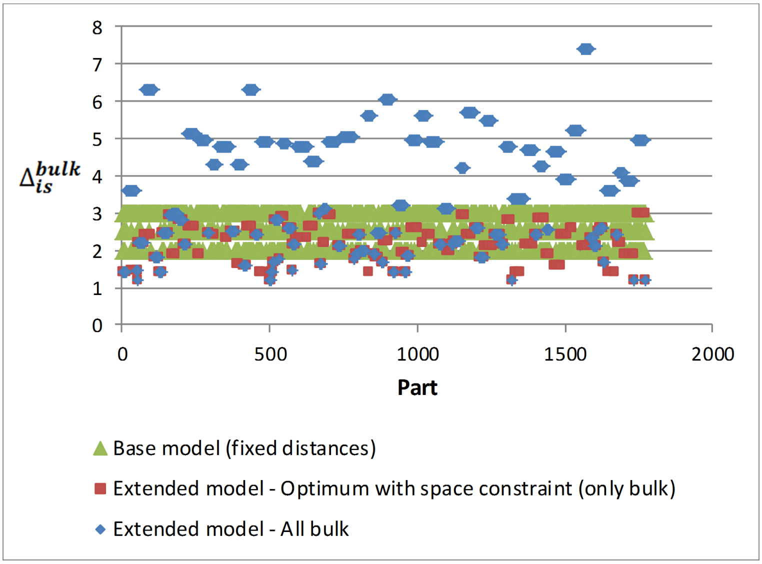


Figure 4.11: Comparison of Δ_{is}^{bulk}

what harder to compare because the assignment of parts to their optimal line feeding method is different for both models. Consequently it is logical that the costs are also different. To start, we observe that even without a space constraint the extended model will assign 36% of the parts to a kitting scenario. In contrast to the base model, a space constraint is no longer a requirement to make kitting an attractive solution. This can easily be justified by the previous figure. Because Δ_{is}^{bulk} values can be very high for the 'all bulk'-scenario, it is beneficial to kit part of the line stock in order to shorten operator walking distances. Although the line picking cost for this optimal case without space constraint solved with the extended model is smaller than the line picking cost for the base model, the transport cost increases a bit and there are additional kitting and replenishment costs, leading to a higher total cost.

For the optimal solution with space constraint the extended model (56%) proposes more kitting than the base model (42%). This is an increase of 33% in the percentage of kitting. Nevertheless, the number of kits needed only goes up by 10%, from 50 to 55 kits. This implies that the kits will be denser. Figure 4.12 shows the space that is used along the border of the line (BoL) of each of the stations for the optimal solution with space constraint versus the 'all bulk' solution. Two things can be remarked. First of all, there are two stations for which the original space needed is below the space constraint of 8 meters, and still kitting is done. This is recognized because the space needed under the optimal solution is even smaller than the original space needed. Secondly, the degree of free riding is larger than for the base model. The average space needed in the optimal solution for this model is only 4.3 m while for the base model it was 5 m. This is due to the splitting up of the kitting cost into a fixed cost and a variable cost. As part of the kitting cost is accounted for in the fixed cost, the variable costs per part are lower. This leads to more parts being chosen to be kitted once the fixed cost is already incurred anyway.

A final effort we make to better understand the differences between both models is to take a look at the cost evolution if the percentage of kitting changes (Figure 4.13). For the generation of data points below 70% of kitting the CPLEX solver runs out of memory. Therefore, we drew a hypothetical trendline representing the expected evolution of total costs. It might be that the real trend in total costs evolving towards 0% of kitting is steeper or more moderate instead, but we are not really interested in the left side of the graph. For the real costs we can see that a similar increase in total costs is observed above 70%, analogous to the cost evolution for the base model.

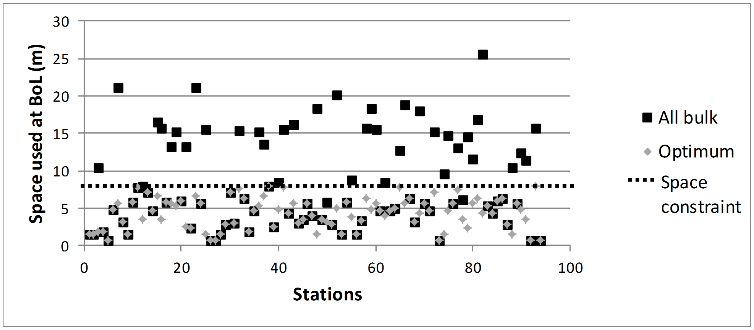


Figure 4.12: *Length used at the border of line of the stations - Extended model*

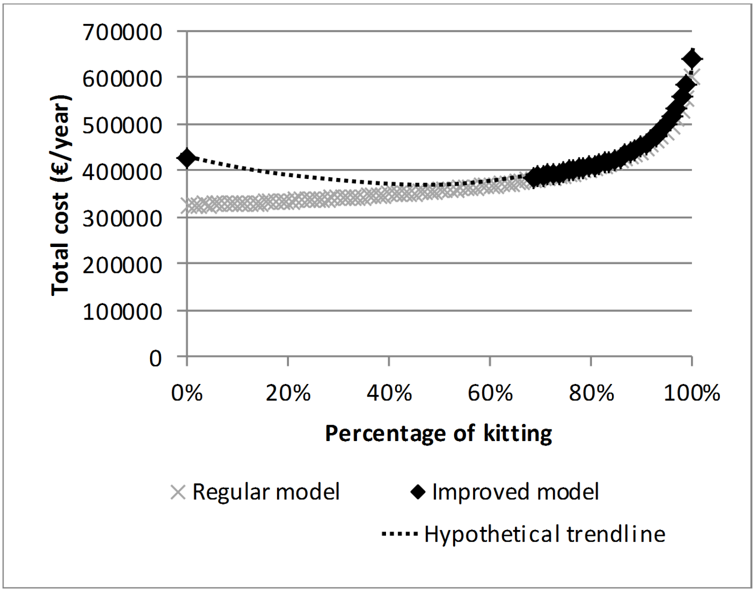


Figure 4.13: *Total cost as the percentage of kitting changes - Extended model*

Zooming in on the costs again gives us more insight (Figure 4.14). In the case of all bulk, two third of the costs consists of picking costs, and only one third are transport costs. On the other hand, when all parts are kitted transport takes credit for half of the costs (50%), kitting accounts for more than one fourth (27%) and the remaining quarter depends on picking at the line (15%) and supermarket replenishment (7%). The major influence thus comes again from transport and kitting costs. In Chapter 5 additional experiments will be discussed further identifying the causes of this cost increase.

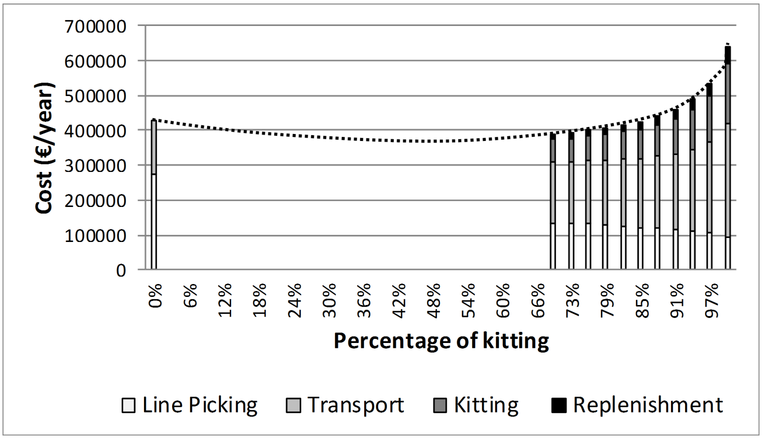


Figure 4.14: *Detail of the cost subdivision as the percentage of kitting changes - Extended model*

4.5 Conclusion

In the base model introduced in Chapter 2, it was not taken into account that a solution, assigning all parts to one of both materials supply systems, has an effect on the average operator walking distance to pick from the border of line. However, operator walking distances have a substantial impact on the solution. In this Chapter, we have adjusted the model to take this additional dependency into account. Moreover, we showed some results pointing out the changes between both models. The results also indicate that the new picking and kitting cost formulations are an improvement over the former. Therefore in the next chapter we will do the computational testing and sensitivity analyses primarily based on this new model.

5

Computational Results

This chapter demonstrates the value of our model. First in Section 5.1, it is shown how part and product mix characteristics have an influence on the decision to supply in kit or in bulk. The results of some representative datasets are presented and several lessons are learned. Next, in Section 5.2, we illustrate the impact of the materials supply parameters on the solution. A design of experiments is set up to understand the relationship between some overall problem parameters on the one hand and the costs and the percentage of kitting on the other hand.

5.1 Impact of Part and Product Mix Characteristics

This section focuses on the influence of part and product mix characteristics on the decision to kit or supply in bulk.

To understand the analyses in this section it is in the first place important to understand that, as already indicated in Chapter 4, there are two kinds of parts that are kitted. On the one hand, there are parts for which the cost of assembling and transporting the kit is justified because of the gains in picking at the line. These can be called *originally kitted parts*. Originally kitted parts do not have to be single parts; it is also possible that a combination of parts together justifies the cost of transporting a kit. On the other hand, there are parts for which the cost of assembling the kit is justified because of the gains in picking at the line, but the cost for transporting the kit is too high. Nevertheless, when there already is a kit used which has remaining free space, some parts can benefit of 'free transport'. In fact, the cost of transport is already justified by the other parts in the kit. The kitted parts for which only the cost of assembling the kit was justified are then called *free riders*. Hence, it must be understood that the decision to kit a part does not only depend on its own characteristics, but also on the characteristics of other parts within the station with which one can be kitted, and on the opportunity of a part to be a 'free rider'.

Because the combination of parts matters, it is thus not possible to say that a part with certain characteristics will always have to be kitted and another part with different characteristics will never have to be kitted. However, it is possible to analyze if certain characteristics will cause the probability of kitting a part to be higher or lower. In this section we will describe these effects.

To analyze the effects we examine five representative datasets created by use of the algorithm and the characterizing distributions described in Chapter 3. Some information about the five datasets is summarized in Table 5.1. Each of these datasets are solved twice with the extended model, once with and once without a space constraint at the border of the line of the stations. General results for each of the datasets are presented in Table 5.2.

As we have already demonstrated there is a considerable batching effect causing kitted parts to be grouped within kits. This is because it is beneficial that parts within a kit share the transport cost for that

Table 5.1: *Input datasets*

	# parts	**# part families**	**# stations**
Input 1	1815	692	104
Input 2	1826	756	95
Input 3	1755	707	92
Input 4	1768	703	93
Input 5	1741	735	96

Table 5.2: *General results for the five datasets - Extended model*

		Input 1	**Input 2**	**Input 3**	**Input 4**	**Input 5**
Without space constraint	**Total cost**	361 674	468 981	361 654	376 674	432 627
	% of kitting	45.6%	45.6%	44.6%	39.3%	42.6%
	# kits	33	37	33	31	34
	# stations with kitting	32	34	32	30	29
	% of kitting in stations with kitting	77.7%	75.0%	76.5%	74.5%	71.2%
With space constraint	**Total cost**	381 551	487 274	371 866	397 297	455 856
	% of kitting	54.5%	57.4%	51.2%	55.7%	50.7%
	# kits	54	59	44	56	57
	# stations with kitting	44	45	39	45	35
	% of kitting in stations with kitting	77.8%	78.6%	75.8%	77.7%	76.1%

kit. Figure 5.1 illustrates that the more parts go to a station, the higher the chance to have kitting at that station.

To make sure that our results are not influenced by the 'good luck' or the 'bad luck' of a part to belong or not belong to a station where kitting is done, in our analysis we will only include the stations where kitting is done. Parts to be supplied to these stations are included in the study to find out which part and product mix characteristics matter. To get more insight in this concern we will put forward several hypotheses and confirm them by use of data.

To start the analysis, the general results of Chapter 4 are reviewed. Figure 4.5 and 4.14 illustrate that both for the initial model and the extended model, above a certain percentage of kitting the materials supply costs experience a sudden upsurge. It is also illustrated that the main cause of this sudden increase is an equivalent intensification in the costs of transport.

Continuing our search for the root cause of this increase we have investigated the evolution in the number of kits. In Figure 5.2 it is demonstrated that the increase in transport costs comes from an increase in the number of kits that needs to be transported. The parts that have the least tendency to be kitted would thus be the parts that take up a lot of space in a kit. Consequently, savings from the elimination of the transport of the bulk packages are offset by the additional cost of transporting the kits.

Hypothesis 1:
The parts that have the least tendency to be kitted are the parts that take up a lot of space in a kit.

To check hypothesis 1, we analyze the relationship between v_i and the percentage of kitting. Because the eliminated transport costs when a part is kitted differ for parts that are originally supplied in pallets versus parts that are supplied in boxes, and since the distribution of values for v_i also differs between pallets and boxes, we split up our analysis.

We first take a look at the results of the extended model when no space constraint is imposed (Figure 5.3 and Figure 5.4). The results positively confirm our hypothesis that parts with lower values for v_i have a lower chance of being kitted. Only for the fourth dataset the result for boxes is against expectations. We presume that this is a coincidence and believe that another effect can explain why the results here are counterintuitive. This will be confirmed later in this section. We remark that between the groups '$v_i < 200$' and '$v_i \geq 200$'

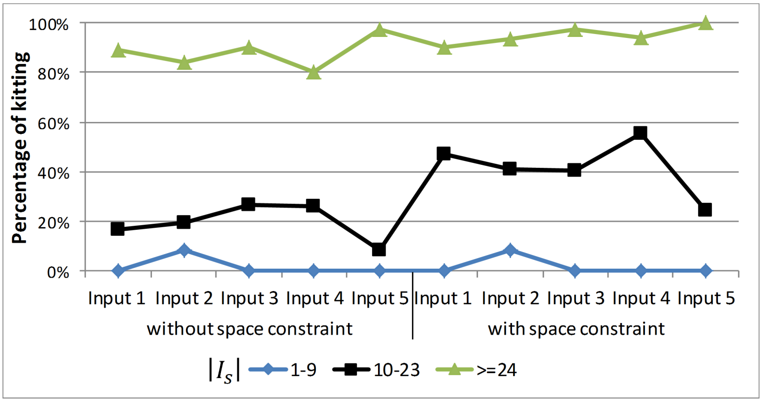


Figure 5.1: *Impact of $|I_s|$ on the percentage of kitting. Extended model*

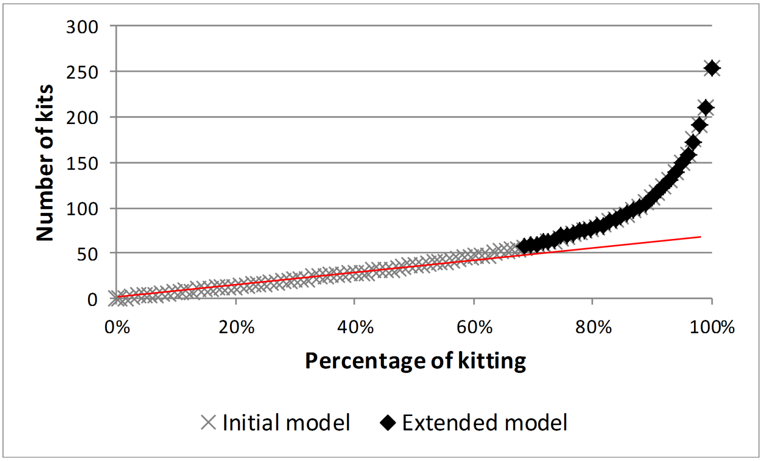


Figure 5.2: *Number of kits (K_s) needed as the percentage of kitting changes.*

the hypothesis is still backed up.

When a space constraint is imposed, the effect put forward is less clear. This makes sense since the supplementary space constraint will mean that not only the parts with minimal extra costs need to be chosen to be kitted, but also the parts that serve to satisfy the space constraint. Figure 5.5 and Figure 5.6 show that the overall percentages of kitting increase due to the space constraint. For pallets, hypothesis 1 is still supported, but for boxes the effect is blurred a bit, indicating that other factors may be at play. Again between the groups '$v_i < 200$' and '$v_i \geq 200$' the hypothesis remains confirmed. The parts with '$v_i \geq 200$' are that small that they often have the opportunity to be 'free riders'.

Space needed at the border of line is a factor that, in the extended model, has a twofold effect. First of all, the space needed at the border of line must satisfy a space constraint. Secondly, the space needed at the border of line determines the walking distances for the assembly operator. Less stock at the line has a positive influence on the space constraint as well as on the walking distances. Therefore, it is assumed that parts that free up a lot of space at the border of the line when they are not stored in bulk at the line, have a higher chance of being kitted. In this regard, we think in the first place of parts that belong to large part families, because they only need space for m_i units in a kit, while many packages are removed from line stock. In the second place, we also remark that it is more effective to remove a pallet from the line stock than a small box. Hypothesis 2 and 3 will be investigated to determine if our reasoning is correct.

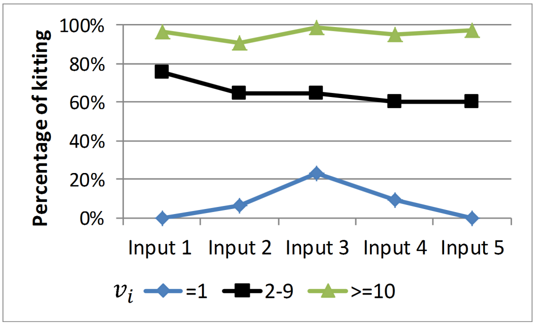


Figure 5.3: *Impact of v_i on the percentage of kitting. Extended model - No space constraint - Pallets*

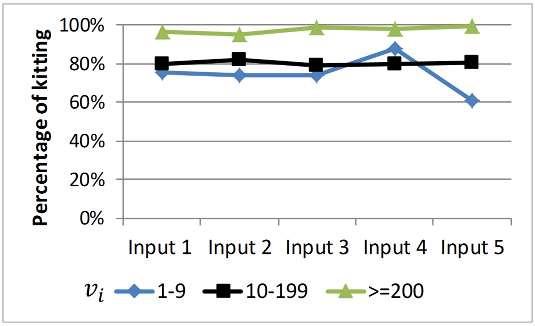


Figure 5.4: *Impact of v_i on the percentage of kitting. Extended model - No space constraint - Boxes*

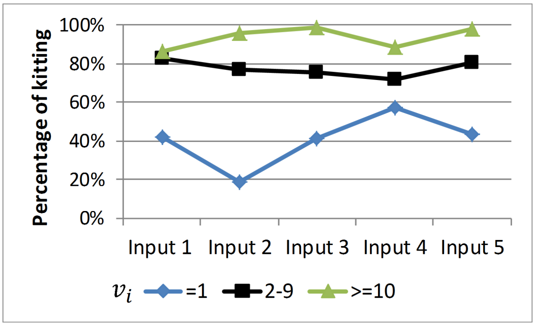


Figure 5.5: *Impact of v_i on the percentage of kitting. Extended model - With space constraint - Pallets*

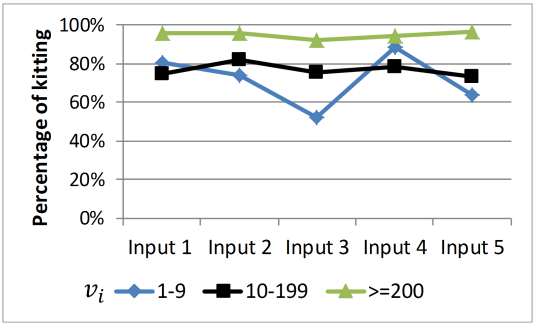


Figure 5.6: *Impact of v_i on the percentage of kitting. Extended model - With space constraint - Boxes*

Hypothesis 2:
The parts that have a higher chance to be kitted are parts that belong to a large part family.

Hypothesis 3:
The parts that have a higher chance to be kitted are parts that are originally packaged in pallets.

Figure 5.7 depicts the percentage of families that are assigned to kitting. We can clearly see that - regardless of whether we solve the model with or without a space constraint - the more parts belong to a part family, the higher the chance of assigning that family to kitting as a preferable method of line feeding. Hypothesis 2 can therefore be confirmed. Moreover, Hypothesis 2 explains why the results for dataset 4 were not backing up hypothesis 1 entirely. For this dataset it can be checked that many parts that are small in volume ($v_i = [1-9]$) belong to large part families ($|V_i| = 16$), i.e. more than on average. Therefore the effect of these parts having more kitting than parts that are medium in volume (($v_i = [10 - 199]$) is to be attributed to hypothesis 2, which takes in this case the upper hand over Hypothesis 1.

Figure 5.8 is set up to validate Hypothesis 3. However, the graph depicts a scenario exactly opposite to what we had expected. Boxes seem to have a higher probability of kitting than pallets. Because all part characteristics are highly correlated we have to be careful in interpreting this cause-effect relationship. In reality it is not the packaging in boxes which leads to a higher probability of kitting, but it is the lower volumes of parts in boxes, i.e. higher values for v_i, which actually cause the counterintuitive outcome. This brings us back to Hypothesis 1. Indeed, only considering the parts with a value of v_i greater than or equal to ten gives a more logical result in Figure 5.9. Even though the distribution of v_i above ten for boxes will still be around higher values of v_i than the distribution for pallets, as expected pallets still have a greater likelihood to be kitted because they free up more space at the border of line. Another difference between pallets and boxes is the difference in transportation. Pallets are transported within the factory walls by forklift trucks. This transport, pallet per pallet, is less efficient than the transport of boxes in milk run tours. The preference to kit pallets rather than boxes might therefore also have to do with the transport costs.

The parameter θ_{is} is also an important parameter in the model since it determines the efficiency of the kitting activity. θ_{is} is defined in Chapter 2 (equation 2.8).

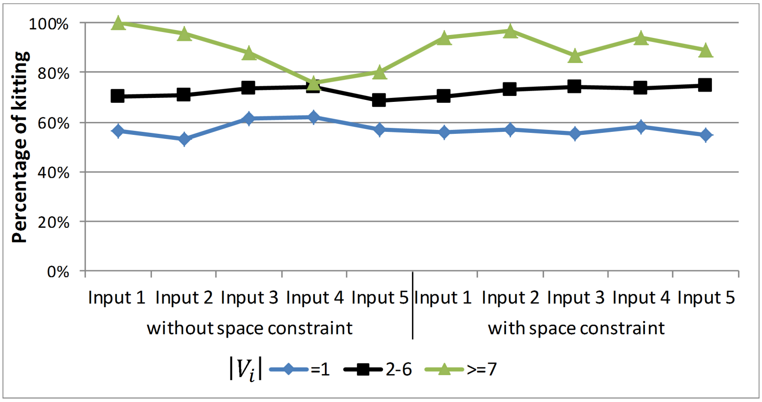


Figure 5.7: *Impact of $|V_i|$ on the percentage of kitting. Extended model*

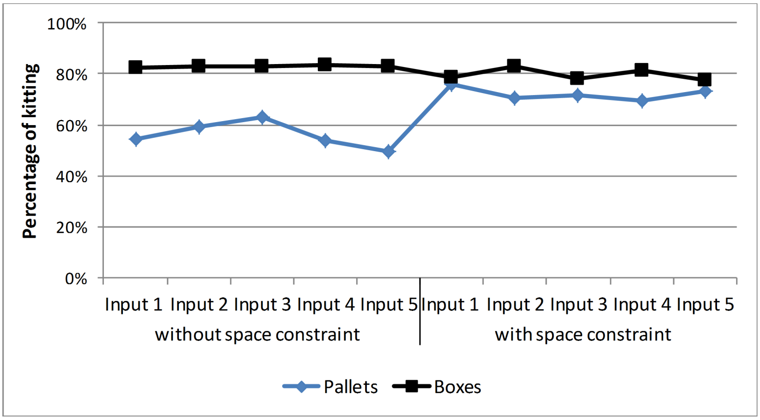


Figure 5.8: *Impact of the supplier packaging on the percentage of kitting. Extended model*

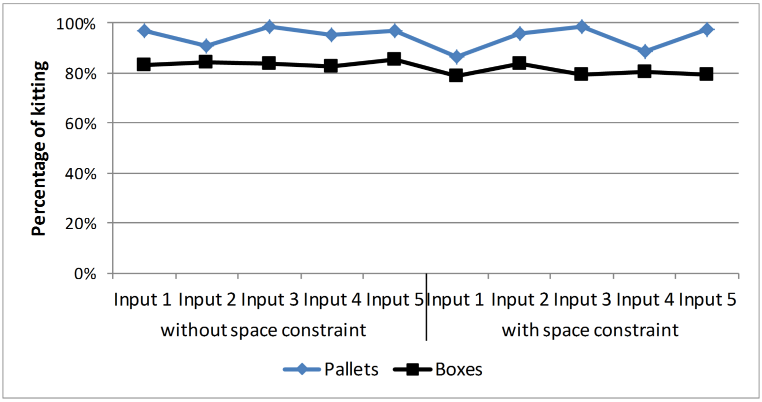


Figure 5.9: *Impact of the supplier packaging on the percentage of kitting. Extended model -* $v_i \geq 10$

We expect an outcome as postulated in Hypothesis 4.

Hypothesis 4:
The parts that have a higher chance to be kitted are parts that have a higher θ_{is}.

Figure 5.10 clearly shows that our hypothesis is true. The higher θ_{is}, the greater the probability of kitting. Since θ_{is} is partly defined by the size of a part, i.e. how many parts can physically be picked in one pick, a portion of this effect is in accordance with Hypothesis 1. Nevertheless, θ_{is} is also defined by the usage of the part, which will also influence if one can take advantage of the physical opportunity to be able to pick more than one part at a time.

Until now, we have looked at the effect of product mix by looking at the impact of the cardinality of a family, we have looked at the size of a part, and we checked for the impact of the packaging. The effect of the yearly usage of a part is not yet investigated. In Figure 5.11 it is demonstrated that parts with a higher yearly usage have a lower possibility of being assigned to kitting as a line feeding method. The reason for this is quite important. When choosing parts to be kitted, it has to be kept in mind that kitting is a costly solution. Parts need to be double handled, once by the kitting operator, and once by the operator at the line and this is expensive. Of course the reward for this double handling are the shorter walking distances at the line. But, kitting does not only shorten the walking distances towards the part that are kitted, but also towards the remaining parts in bulk. Therefore, it is more beneficial to kit parts for which the usage is low, and thus also the double handling is limited. As such the border of

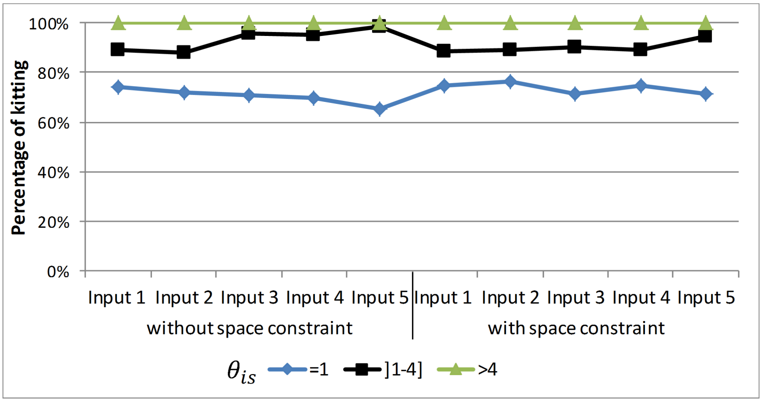


Figure 5.10: *Impact of θ_{is} on the percentage of kitting. Extended model*

the line will also shrink and high usage parts, still packaged in bulk, can be positioned closer to the location where they are needed as well.

The hypothesis we have confirmed is thus the following:

Hypothesis 5:
The parts with a higher (yearly) usage q_{is}, have a lower probability to be kitted.

We have now explained how part characteristics matter in the choice of the most appropriate line feeding system. However, we must reiterate that not only the part characteristics of a part itself matter, but also the characteristics of the parts that can be kitted with it. More specifically the mix of parts has a great influence on the choice of line feeding system. If a kit can be composed such that almost no free space is left over in the kit and that many bulk transports are saved in return for one kit transport, kitting will take place. Often it is thus not so much the characteristics of parts that matter but rather the coincidental good fit of all parts together in a kit. This insight combined by the understanding generated by the five hypotheses stated above will support logistics and production engineers in assigning parts to material flows.

5.2 Impact of Materials Supply Parameters

In the experiments presented in the previous section, we have worked with the materials supply parameters from the case study. These have

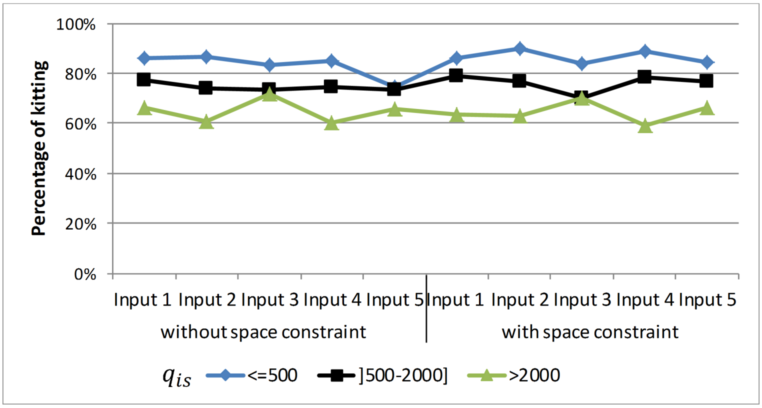


Figure 5.11: *Impact of the yearly usage on the percentage of kitting. Extended model*

been discussed in Chapter 3 and are summarized in Table 3.1. These parameters however are case specific. In this section we want to find out how these parameters influence the solution. Therefore a design of experiments is set up. The test instances are generated according to a 10×2^4 factorial design. This is an experimental design in which 4 factors are considered, each at two levels, and in which for each possible combination of the factors 10 instances are created. The four factors and their levels concerned in the study are given in Table 5.3. The factor levels are binary coded with the lower level of each factor assigned to '0' and the higher level of each factor assigned to '1'.

The first factor investigates the impact of workstation layout. The parameter Δ^k is the average distance for the line-operator to pick from a kit. In the original setting the kit was positioned at 1.5 m from the operator. To investigate the impact on the solution if the kit can be positioned closer, a lower level of 'Δ^k=0.5 m' is considered.

The second factor investigates the impact of the plant layout. The parameter D^k is the distance of the milk run tour for kits. In the orig-

Table 5.3: *Values for the materials supply parameters in the factorial design.*

Parameter	Level 0	Level 1
Δ^k	0.5 m	1.5 m
D^k	1640 m	2460 m
τ^k and τ^{bulk}	0.00015 h	0.0003 h
B^k	1	5

inal setting the supermarket was positioned at the same distance from the line as the small box warehouse - Δ^k=1640 m. To examine the impact of a lack of space close to the line we assume the supermarket will be positioned further away from the line and the milk run tour will be longer. The second level for Δ^k is set higher at 2460 m.

The third factor is chosen to examine the impact of operator productivity and the effect of the installation of picking technologies as 'pick to voice' and 'pick to light'. The parameter τ^k is the average time to search for the required part from bulk stock in the supermarket and τ^{bulk} is the average time to search for the required part from bulk stock at the line. In the original setting both search times were fixed at 0.0003 h or 1.08 seconds. In our design of experiments the second level for both parameters is set at a lower value of 0.00015 h or 0.54 seconds considering that search times can considerably be reduced if picking technologies are used. Since there was no reason to believe that a picking technology can better be implemented at the kitting area than at the line, both search times are adjusted equally.

The fourth and last factor considers the productivity of the kitting operator in the supermarket. The parameter B^k is the batch size for assembling kits. In the original setting it is assumed that 5 kits are collected at once. In a second level for B^k we consider that kits are collected one by one instead of in batches. This factor is included to detect how much can be gained by batch picking at the supermarket.

For each combination of the factors 10 instances are generated by use of the algorithm and the characterizing distributions described in Chapter 3. All 160 ($= 10 \times 2^4$) instances are solved twice, once with and once without a space constraint. The space constraint is also coded as a binary variable with absence of a space constraint assigned to '0' and presence of a space constraint assigned to '1'. Table A.1 of Appendix A gives an overview of the features of the datasets. Table A.2 of Appendix A gives the individual results for all these instances.

To evaluate how the materials supply parameters influence the optimal solution, two stepwise linear regression analyses are performed. The first analysis investigates the impact of the factors on the percentage of kitting, while the second one investigates the impact of the factors on the total costs of the optimal solution. The independent variables are the four factors chosen in the design of experiments, supplemented with the binary variable representing the space constraint and the three descriptive parameters of the input datasets - the number of parts, the number of stations and the number of families. Table 5.4 and Table 5.5 present the models obtained. The adjusted R-squares of both models are respectively 0.843 and 0.563. The models are also checked with inclusion of interaction effects but since adding these has a negligible effect on the adjusted R-squares - 0.843 increases to 0.867 and 0.563 increases to 0.577 - they are not included here.

The first model, examining the impact on the percentage of kitting, shows that the factors with a significant effect are the space constraint, Δ_k, D_k and all three descriptive parameters of the input datasets. The excluded factors are thus τ and B^k. The value for the adjusted R^2 is high; the model explains 84% of the variance. For the three descriptive parameters of the input datasets - the number of parts, the number of stations and the number of families - we must remark that the coefficients in the regression analysis give the change in costs for the increase of each of these parameters with one unit. Since in our datasets the number of parts ranges from 1703 to 1866 parts, the number of stations varies from 78 to 111 stations and the number of part families is between 630 and 781 the coefficients should only be applied within these ranges. For example a change in the number of stations from 80 to 83, ceteris paribus, is expected to decrease the percentage of kitting with almost 1 percent (-0.972%). This makes sense, because when there are more stations, each station will have less parts and the opportunity to create good kits is smaller. A change in the number of parts from 1750 to 1800, ceteris paribus, is expected to increase the percentage of kitting with more than 1 percent (+1.05%). This similarly makes sense, because when there are more parts, each station will have more parts and the opportunity to create good kits is larger. The same effect is experienced if the number of part families increases, ceteris paribus. More part families will lead to an increased percentage of kitting.

The second model, examining the impact on the total costs, shows that the factors with a significant effect are the space constraint, Δ_k, D_k, τ, B^k and the number of part families in the dataset. The excluded factors are thus the number of parts and the number of stations. The value for the adjusted R^2 is moderate; the model explains 56% of the variance. Again a remark is made for the inclusion of the number of part families in the regression. The coefficients should only be applied within the ranges of part families going from 630 to 781.

For the space constraint, Δ_k, D_k, τ and B^k, each of the significant effects will now be discussed in detail. We must reiterate that these are all binary factors. The coefficients in the regression thus give the change in the dependent variable when the factors change from their

Table 5.4: *Regression analysis - Percentage kitting.*

Model	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	26.709	11.836		2.257	0.025
space constraint	15.18	0.43	0.784	35.326	0
Δ_k	-6.339	0,43	-0.327	-14.738	0
D_k	-5.324	0,431	-0.275	-12.364	0
number of stations	-0.324	0.035	-0.208	-9.313	0
number of parts	0.021	0.007	0.074	3.212	0.001
number of families	0.021	0.008	0.062	2.693	0.007

Coefficients[a]

a. Dependent Variable: % kitting

Table 5.5: *Regression analysis - Total cost.*

Model	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	44104.675	34315.892		1.285	0.2
Δ_k	30590.944	2688.93	0.421	11.377	0
space constraint	25783.8	2688.649	0.355	9.59	0
D_k	24627.333	2692.772	0.339	9.146	0
number of families	407.033	48.229	0.315	8.44	0
τ	12209.898	2693.072	0.168	4.534	0
B^k	-6686.169	2702.617	-0.092	-2.474	0.014

Coefficients[a]

a. Dependent Variable: Total cost

lower level to their higher level.

5.2.1 Space Constraint

In Figure 5.12 and Table 5.6 the effect of the space constraint on the solution characteristics is shown. Since an extra constraint is imposed, the total costs increase, and this on average with €25784. The cause of the cost increase is an increased percentage of kitting (+15.2%). Parts that are originally not assigned to kitting are now kitted in order to free up the necessary space at the line. When we look at the subcosts we notice that the transport cost for boxes is hardly lower than before. The transport cost for pallets on the contrary has decreased considerably. This demonstrates that the parts that are shifted from bulk to kitting are mainly parts originally packaged in pallets. This matches with our believe that parts on pallets free up more space at the line, but also that they are often larger and therefore occupy more space in a kit. An additional space constraint adds more value to the benefit of freeing up space at the line and thus justifies the transport costs of the additional kits. Finally we notice that there also is a considerable increase in stations where kitting is done (+13.7%). The additional kitting must be done in stations where the space constraint is binding, so it is more difficult to take advantage of batching effects.

5.2.2 Average Distance to Pick from a Kit

In Figure 5.13 and Table 5.7 the effect of a change in Δ^k on the solution characteristics is shown. Since a cost related factor is decreased ceteris paribus, the total costs decrease. On average the total costs decrease with €31077. The cost decrease goes together with an increased percentage of kitting (+6.3%). Kitting has become cheaper and therefore for more parts kitting becomes the preferable materials supply method. Even though more kitting is done, the cost to pick from kits has decreased because of the reduced walking distance. When we look at the subcosts we notice that the transport cost for boxes has decreased much more than the transport cost for pallets. This demonstrates that the parts that are shifted from bulk to kitting are mainly parts originally packaged in boxes. Parts originally packaged in pallets and not assigned to kitting as the preferable line feeding method are mostly large parts. The additional cost to transport these parts in kits would offset the gain in line picking.

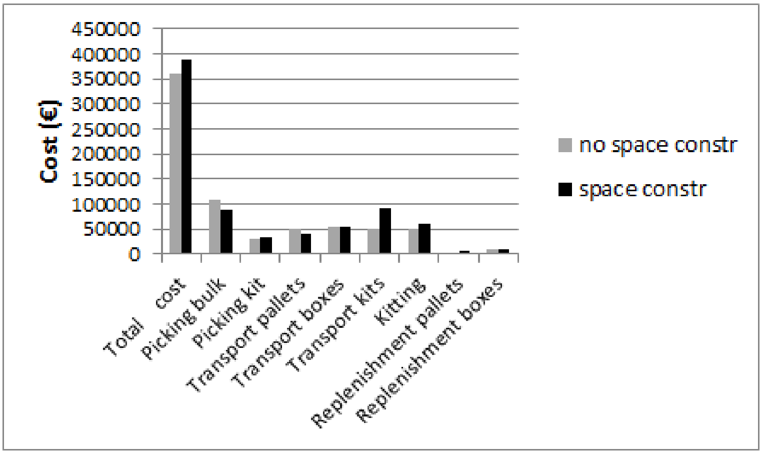


Figure 5.12: *Effect of the space constraint on costs.*

Table 5.6: *Effect of the space constraint.*

	without space constraint	**with space constraint**
Total cost	361779	387562
Picking bulk	108571	88112
Picking kit	29915	32727
Transport pallets	51545	41403
Transport boxes	55818	54947
Transport kits	52246	91604
Kitting	51750	62880
Replenishment pallets	2299	5999
Replenishment boxes	9633	9889
% kitting	42.9%	58.0%
Number of kits	34	58
% stations with kitting	33.4%	47.1%

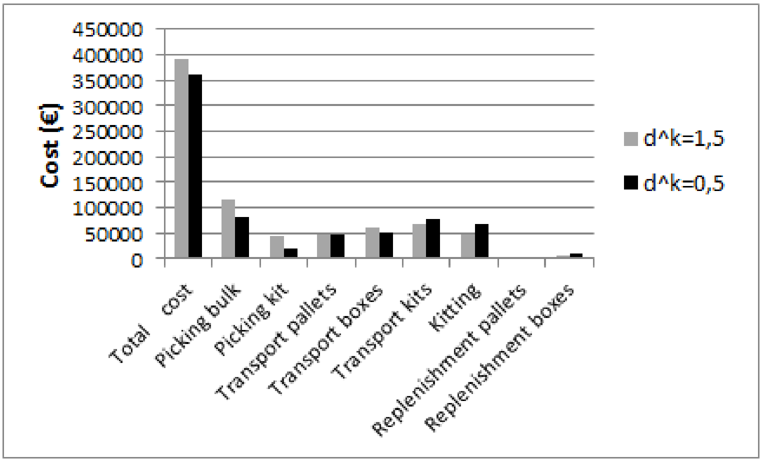


Figure 5.13: *Effect of the average distance to pick from a kit on costs.*

Table 5.7: *Effect of the average distance to pick from a kit.*

	$\Delta^k = 1.5$	$\Delta^k = 0.5$
Total cost	390209	359132
Picking bulk	114286	82398
Picking kit	42540	20102
Transport pallets	46013	46936
Transport boxes	61042	49723
Transport kits	66604	77246
Kitting	47604	67027
Replenishment pallets	4157	4141
Replenishment boxes	7962	11560
% kitting	47.3%	53.6%
Number of kits	43	49
% stations with kitting	37.8%	42.7%

5.2.3 Distance of the Milk Run Tour for Kits

In Figure 5.14 and Table 5.8 the effect of a change in D^k on the solution characteristics is shown. Since a cost related factor is increased ceteris paribus, the total costs increase. On average the total costs increase with €26158. The cost increase goes together with a decreased percentage of kitting (-5.3%). Kitting has become more expensive and therefore for more parts bulk feeding becomes the preferable materials supply method. Even though transporting kits has become more expensive, the cost to transport kits has decreased due to the reduced amount of kitting. When we look at the subcosts we notice that the transport cost for boxes has increased while the transport cost for pallets has decreased. This demonstrates that the parts that are shifted from kitting to bulk are mainly parts originally packaged in boxes.

5.2.4 Searching Times

In Figure 5.15 and Table 5.9 the effect of a change in τ^k and τ^{bulk} on the solution characteristics is shown. Since a cost related factor is decreased ceteris paribus, the total costs decrease. On average the total costs decrease with €11261. The decrease in costs is limited and no significant change in the percentage of kitting is seen. The cost of picking from bulk and the cost of kitting obviously decrease since the time for the operator to search for the correct part is halved. Although the percentages of kitting are not significantly different, the mix of the parts in kits might still change a bit due to the change in the searching times.

5.2.5 Kit Batch Size

In Figure 5.16 and Table 5.10 the effect of a change in B^k on the solution characteristics is shown. Since the efficiency of kitting is lowered ceteris paribus, the total costs increase. On average the total costs increase with €8663. The increase in costs is limited and no significant change in the percentage of kitting is seen. The cost of kitting obviously increases since kitting is not carried out in batches anymore. Although the percentages of kitting are not significantly different, the mix of the parts in kits might still change a bit due to the change in kitting efficiency.

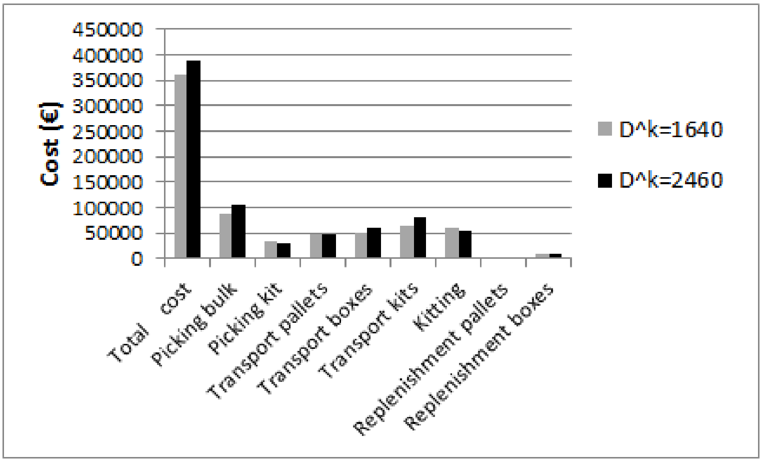


Figure 5.14: *Effect of the distance of the milk run tour for kits on costs.*

Table 5.8: *Effect of the distance of the milk run tour for kits.*

	$D^k = 1640$	$D^k = 2460$
Total cost	361428	387586
Picking bulk	90125	106356
Picking kit	33277	29414
Transport pallets	46889	46070
Transport boxes	50775	59876
Transport kits	63292	80345
Kitting	61720	53019
Replenishment pallets	4306	3997
Replenishment boxes	11044	8510
% kitting	53.1%	47.8%
Number of kits	50	42
% stations with kitting	42.7%	37.8%

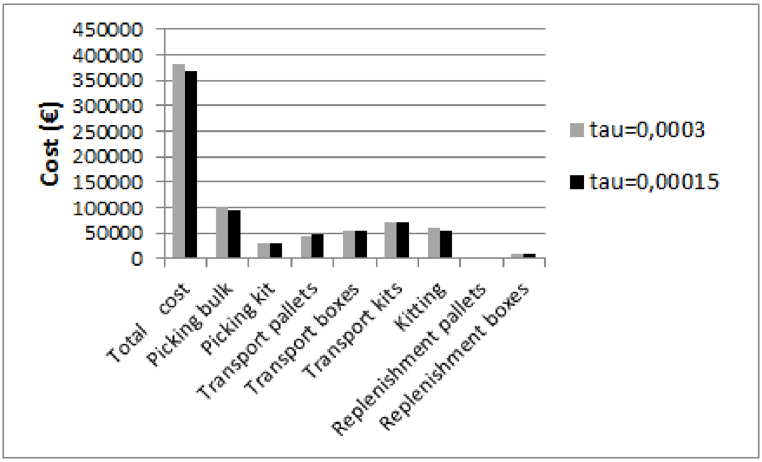


Figure 5.15: *Effect of the searching times on costs.*

Table 5.9: *Effect of the searching times.*

	$\tau = 0.0003$	$\tau = 0.00015$
Total cost	380301	369040
Picking bulk	102096	94588
Picking kit	31575	31067
Transport pallets	44829	48119
Transport boxes	55360	55405
Transport kits	71995	71855
Kitting	60471	54160
Replenishment pallets	4187	4112
Replenishment boxes	9788	9734
% kitting	50.5%	50.4%
Number of kits	46	46
% stations with kitting	40.3%	40.2%

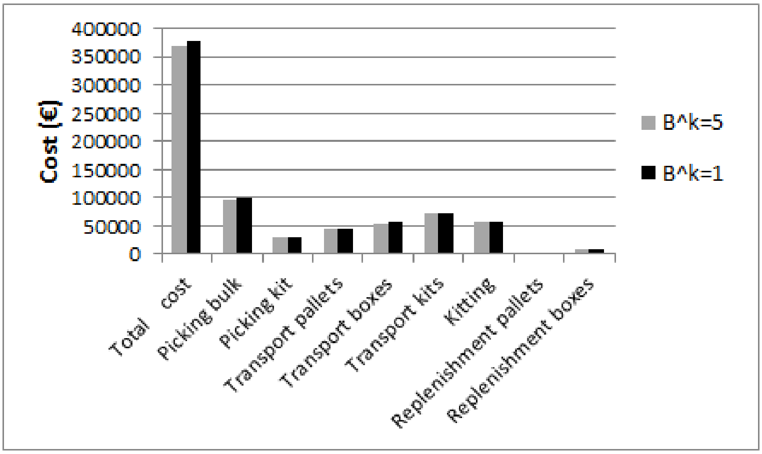


Figure 5.16: *Effect of the kit batch size on costs.*

Table 5.10: *Effect of the kit batch size.*

	$B^k = 5$	$B^k = 1$
Total cost	370339	379002
Picking bulk	96987	99696
Picking kit	31433	31209
Transport pallets	46257	46692
Transport boxes	53266	57500
Transport kits	72218	71632
Kitting	56290	58341
Replenishment pallets	4212	4087
Replenishment boxes	9677	9845
% kitting	50.9%	50.0%
Number of kits	46	46
% stations with kitting	40.5%	39.9%

5.3 Conclusion

In this chapter we have done some testing on real size problem instances to investigate in which situations kitting is preferred over line stocking and vice versa. Firstly, in section 5.1 it is shown that certain parts are preferred over others to be kitted. Therefore, to obtain a cost-effective solution it is important to carefully consider which parts are assigned to which materials supply system. Secondly, in section 5.2 the design of experiments shows how changes in materials supply parameters can be quantified as a cost, and the impact on the percentage of kitting is given.

6 Conclusion

This dissertation deals with the materials supply of mixed-model assembly lines. In industry, one can find many diverse materials supply systems. Two opposites in this spectrum of materials supply systems are bulk feeding and kitting. This dissertation describes the first mathematical optimization model that supports the strategic choice between bulk feeding and kitting and provides a theoretical basis for hybrid materials feeding policies. The model directly addresses the selection process between kitting, partial kitting, and bulk feeding (i.e. no kitting).

6.1 Review of Research Questions

This section shows how the research questions, presented in Chapter 1, have been answered.

> ***Research question 1:***
> *What are the costs and benefits associated with kitting and line stocking?*

To answer this first research question both part feeding systems have been investigated in industry. Experience is gained by observing both systems in practice and discussing issues with logistics experts. Moreover, a literature review has been done. Advantages and disadvantages of different part feeding methods are discussed in Chapter 1 and pros and cons for kitting and line stocking are listed in Table 1.1. In Chapter 2 both part feeding systems are analyzed in detail and for each system the material flows are discussed. All separate material flows are examined and cost formulations are set up capturing the trade-offs for each system. In Chapter 4, for two of the material flows - picking at the line and kitting - the cost formulations are further refined.

> ***Research question 2:***
> *Can we solve the cost model to optimality in order to assign all stock keeping units to a certain method of line feeding in an overall cost-effective way?*

Based on the cost formulations a mixed integer linear programming model is developed to do the assignment of parts to their most appropriate line feeding method. The mathematical model presented in Chapter 2 and the extension in Chapter 4 are implemented using the modeling language AMPL 11.2, and solved with CPLEX 11.2 on an Intel Centrino Duo 1.67 GHz with 2 GB RAM memory. Run times are very short and are in the range of 0-10 seconds for real size instances (around 1800 parts going to about 100 stations).

The model has shown that the in-plant logistics costs for kitting - i.e. the costs of the material flows from the warehouse to the use-point at the line - are more expensive than the in-plant logistics costs for line stocking. Kitting is a more expensive solution since material is handled by the kitting operator before it is transported to the line. It is then handled a second time by the operator at the line. This double-handling has often been seen as a waste and is the main argument of the opponents of kitting. However, with regard to assembly, kitting has a major advantage in reducing the amount of inventory at the border of the line. Since the border of the line becomes less crowded, the walking distances of the operators decrease and operator efficiency increases.

As a consequence the model demonstrates that kitting to a certain degree is beneficial. Not only operator walking distances towards parts within kits are reduced, but also the walking distances towards the remaining parts in bulk are shortened due to the reduction in stock at the border of the line. To prevent the high in-plant logistics costs of kitting from canceling out the gain in operator efficiency at the line, the parts that are kitted must be selected with care.

> ***Research question 3:***
> *How do part and product mix characteristics influence the choice of the appropriate line feeding method?*

An analysis is performed to investigate the impact of part and product mix characteristics on the solutions. In order to do this analysis and obtain generalizable results multiple datasets are needed for testing. In Chapter 3 an algorithm is developed in VBA to create synthetic datasets based on real data from a case study. In Chapter 5, section 5.1, the study of the impact of part and product mix characteristics is reported. Some interesting conclusions are obtained:

- The parts that have the least tendency to be kitted are the parts that take up a lot of space in a kit.
- The parts that have a higher chance to be kitted are parts that belong to a large part family.
- The parts that have a higher chance to be kitted are parts that are originally packaged in pallets.
- The parts that have a higher chance to be kitted are parts that have a higher θ_{is}.
- The parts with a higher (yearly) usage q_{is}, have a lower probability to be kitted.

Furthermore, it needs to be stressed that above the individual part characteristics the mix of parts that can be grouped into a kit, and the good or bad fit between those parts has an important impact on the decision to kit or not to kit.

> ***Research question 4:***
> *How do plant design characteristics and kitting organization influence the choice of the appropriate line feeding method?*

In Chapter 5, section 5.2, the analysis to examine the impact of plant design characteristics and kitting organization is reported. The parameters investigated are the space constraint, the average distance for the line-operator to pick from a kit (Δ^k), the distance of the milk run tour for kits (D_k), the average time to search for the required part from bulk stock at the line and in the supermarket (τ^{bulk} and τ^k) and the batch size for assembling kits (B^k). A regression analysis is carried out to quantify the impact of each of these factors.

> ***General research question:***
> *Can we gain insight into the factors that determine the optimal assignment policies of parts to an appropriate material supply method - kitting or line stocking?*

This research has greatly increased our understanding of the trade-offs between kitting and line stocking. Overall, we have added scientific knowledge by providing a comprehensive view of the different aspects of line stocking and kitting within one research design, and by testing it in an empirical setting.

The model that is developed can be used in the first place to assign parts to their preferable method of line feeding. This is the main objective of the model. However, the model can also be used to study many trade-offs. A company might want to examine which material equipment should be purchased. They can consider different options, for example two tuggers with a different capacity to pull kits to the line and different expected capacity utilizations. When inputting the characteristics of these two options in the model, the alternative total costs will be obtained and this information can be used to make a well balanced investment decision. In the same way different material equipment might also be considered at the line. Storing boxes in Lean lifts for example will reduce the space needed to store boxes in bulk along the line. This in turn will diminish the need for kitting and thus lower costs. This reduction in costs can be compared to the costs of the new equipment to check if the investment is worth it. Furthermore, kit containers or racks can be chosen in different sizes, with different capacities and corresponding costs; new picking technologies can be purchased such as 'pick to voice' and 'pick to light'; and so on. Each of these choices can be evaluated likewise.

The model can also state the cost of a space constraint, by running the model first with and then without the space constraint and evaluating the cost difference. This can be interesting since it puts forward the usefulness of integrating the decision of materials supply with line balancing. As a matter of fact, the space needed at a station is connected with the way tasks are assigned to stations. A change in the way the line is balanced can thus have an important impact on the way material should optimally be supplied.

6.2 Further Research

The literature on part supply of mixed-model assembly lines mostly consists of studies focusing on one specific method of line feeding. This research is the first study really tackling the problem of determining an overall optimal materials supply strategy. The topic of materials feeding is so wide and unexplored that many studies should follow. In this section we give some interesting directions for future research.

Traveling Kits

This research studies stationary kits. A stationary kit is delivered to a workstation and remains there until it is depleted. In practice aside from stationary kits, traveling kits are observed. A traveling kit moves along with the end product and feeds several workstations before it is depleted. Our model is highly generic and can easily be extended to accommodate traveling kits. In this case there is only one volume and one weight constraint for kits over all stations. There is no longer one use-point per station but only one use-point at the start of the line or several use-points spread over the line if more than one transport kit is depleted over the full assembly line.

Considering Automation of Materials Handling Systems

At the moment only operational running costs are included in the model. This is acceptable since we focus on manual materials handling systems. As no automation is considered, investment costs will be low compared to the cost of labor and are assumed to be negligible. In future research it will be interesting to extend the model to situations with automation. Transport can be automated by use of conveyors or Electric Monorail Systems (EMS). Moreover Lean lifts or carousels can be installed at the line or in the supermarket, having severe impacts on picking times and space requirements. If automated systems are assumed, the investment costs should be included in the analysis.

Centralization of Stock

Battini et al. (2009) already recognized that the material centralization/decentralization decision and the assembly line feeding problem need an integrated approach. In this research we only studied the situation with centralized warehouses and a centralized supermarket. This research can be extended by incorporating the possible decentralization of stock.

Effect on Quality and Line Stoppages

Next to the direct effects on material handling costs, kitting also has multiple effects on quality. Since a kit may actually resemble a 'loosely assembled' product (Bozer and Mcginnis, 1992), a potential increase in product quality is expected. For components that look alike, the risk of assembling the wrong part is eliminated as the operator does not need to look for the correct component anymore. Given that the kit package is properly designed, it will also be easy to notice if a component is missing (Schwind, 1992). All of this has a positive impact on the end product quality. Also the quality of raw materials supplied to the line is improved. It is avoided that parts are lying idle in open packages at the border of the line, minimizing the risk of damage (Schwind, 1992).

With regard to delayed assembly and line stoppages it is argued that line stocking grants the advantage of having a safety stock near the line. If a part is damaged, another part can be taken from the container and production can proceed without any problem. However, if parts or kits are sequenced, no safety stock is available. If wrong parts are kitted or defective parts are encountered, the line may have to be stopped. However on the other hand, quality checks will take place earlier in the value chain. Problems can thus often be detected in time and solutions can be found before the stock is needed at the line. The effect on quality and line stoppages thus highly depends on the degree of error-free kitting.

The opposing effects described above have an important impact on the trade-offs in our model. Therefore it is an important avenue for further research to study these effect and quantify them. This will make it possible to include them in the cost model.

The Use of Different Research Methodologies

In this study a mathematical model is used to analyze a materials supply system. Different research methodologies, such as simulation, case studies and experimental mock-ups can be used to study this problem as well. These studies could generate additional interesting insights from another viewpoint, and could moreover be used for validating our model.

Integrating Materials Supply and Assembly Line Balancing

As we have mentioned at the end of the previous section a change in the way the line is balanced can have an important impact on the way material should optimally be supplied. This suggests integrating the line balancing and the materials supply problem. Boysen et al. (2007) do also recognize the need to solve the line balancing and material supply problems simultaneously. A first effort in integrating both problems has been made by Bautista and Pereira (2007). They introduce a new family of variant problems of the assembly line balancing problem in which space allotted to materials and to manufacturing and assembly tools is taken into account, i.e. Time and Space constrained Assembly Line Balancing Problems (TSALBP). This problem works with a fixed required space for each task j represented by a_j. They do not include different values for a_j depending on the materials supply system chosen. This will be an interesting extension.

Outsourcing

This study focuses on the effects of kitting and line stocking within the factory walls. In chapter 1 we have already mentioned that materials handling activities can take place at different points in the supply chain. Kitting and sequencing do not have to be performed in-plant but can be outsourced to a 3PL or to the suppliers. Within this regard Klingenberg and Boksma (2010) propose a conceptual framework for outsourcing of materials handling in the automotive industry. More research on the impact of this outsourcing decision on the trade-offs between line stocking and kitting is encouraged.

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A

Computational Results

Table A.1: *Impact of materials supply parameters - Input*

	number of parts	number of stations	number of families	Δ^k	B^k	τ^{bulk}/τ^k	D^k
Input 1	1818	95	781	0.5	1	0.00015	1640
Input 2	1718	102	709	0.5	1	0.00015	1640
Input 3	1798	97	678	0.5	1	0.00015	1640
Input 4	1758	98	663	0.5	1	0.00015	1640
Input 5	1707	100	703	0.5	1	0.00015	1640
Input 6	1807	87	709	1.5	1	0.00015	1640
Input 7	1798	85	695	1.5	1	0.00015	1640
Input 8	1791	91	709	1.5	1	0.00015	1640
Input 9	1721	90	712	1.5	1	0.00015	1640
Input 10	1738	93	696	1.5	1	0.00015	1640
Input 11	1841	92	712	0.5	5	0.00015	1640
Input 12	1769	94	713	0.5	5	0.00015	1640
Input 13	1795	86	734	0.5	5	0.00015	1640
Input 14	1770	100	664	0.5	5	0.00015	1640
Input 15	1819	93	708	0.5	5	0.00015	1640
Input 16	1775	88	747	1.5	5	0.00015	1640
Input 17	1750	95	702	1.5	5	0.00015	1640
Input 18	1802	93	698	1.5	5	0.00015	1640
Input 19	1758	97	661	1.5	5	0.00015	1640
Input 20	1795	90	685	1.5	5	0.00015	1640
Input 21	1812	78	724	0.5	1	0.0003	1640
Input 22	1828	103	720	0.5	1	0.0003	1640
Input 23	1773	94	645	0.5	1	0.0003	1640
Input 24	1773	95	688	0.5	1	0.0003	1640
Input 25	1765	94	676	0.5	1	0.0003	1640

Table A.1: *Impact of materials supply parameters - Input (continued)*

	number of parts	number of stations	number of families	Δ^k	B^k	τ^{bulk}/τ^k	D^k
Input 26	1740	94	769	1.5	1	0.0003	1640
Input 27	1774	87	716	1.5	1	0.0003	1640
Input 28	1725	86	738	1.5	1	0.0003	1640
Input 29	1768	91	744	1.5	1	0.0003	1640
Input 30	1777	96	709	1.5	1	0.0003	1640
Input 31	1825	90	707	0.5	5	0.0003	1640
Input 32	1766	99	717	0.5	5	0.0003	1640
Input 33	1780	83	700	0.5	5	0.0003	1640
Input 34	1819	92	719	0.5	5	0.0003	1640
Input 35	1808	92	638	0.5	5	0.0003	1640
Input 36	1753	91	704	1.5	5	0.0003	1640
Input 37	1785	111	747	1.5	5	0.0003	1640
Input 38	1791	97	691	1.5	5	0.0003	1640
Input 39	1777	91	733	1.5	5	0.0003	1640
Input 40	1744	94	678	1.5	5	0.0003	1640
Input 41	1724	104	704	0.5	1	0.00015	2460
Input 42	1780	86	723	0.5	1	0.00015	2460
Input 43	1782	93	728	0.5	1	0.00015	2460
Input 44	1798	92	705	0.5	1	0.00015	2460
Input 45	1774	95	707	0.5	1	0.00015	2460
Input 46	1759	101	700	1.5	1	0.00015	2460
Input 47	1860	101	702	1.5	1	0.00015	2460
Input 48	1782	105	743	1.5	1	0.00015	2460
Input 49	1717	91	733	1.5	1	0.00015	2460
Input 50	1821	89	709	1.5	1	0.00015	2460
Input 51	1813	93	643	0.5	5	0.00015	2460
Input 52	1813	85	730	0.5	5	0.00015	2460
Input 53	1792	81	726	0.5	5	0.00015	2460
Input 54	1801	91	699	0.5	5	0.00015	2460
Input 55	1732	100	692	0.5	5	0.00015	2460
Input 56	1829	92	702	1.5	5	0.00015	2460
Input 57	1814	89	739	1.5	5	0.00015	2460
Input 58	1748	87	736	1.5	5	0.00015	2460
Input 59	1761	91	651	1.5	5	0.00015	2460
Input 60	1777	85	677	1.5	5	0.00015	2460
Input 61	1820	93	700	0.5	1	0.0003	2460
Input 62	1794	93	722	0.5	1	0.0003	2460
Input 63	1757	102	763	0.5	1	0.0003	2460
Input 64	1791	93	711	0.5	1	0.0003	2460
Input 65	1791	91	692	0.5	1	0.0003	2460
Input 66	1777	91	668	1.5	1	0.0003	2460
Input 67	1760	97	664	1.5	1	0.0003	2460
Input 68	1801	92	708	1.5	1	0.0003	2460
Input 69	1823	102	725	1.5	1	0.0003	2460
Input 70	1774	96	699	1.5	1	0.0003	2460
Input 71	1770	107	739	0.5	5	0.0003	2460
Input 72	1817	93	712	0.5	5	0.0003	2460
Input 73	1800	84	710	0.5	5	0.0003	2460
Input 74	1799	96	699	0.5	5	0.0003	2460
Input 75	1792	93	721	0.5	5	0.0003	2460
Input 76	1713	85	685	1.5	5	0.0003	2460
Input 77	1764	91	674	1.5	5	0.0003	2460
Input 78	1797	99	729	1.5	5	0.0003	2460
Input 79	1756	102	682	1.5	5	0.0003	2460
Input 80	1710	82	673	1.5	5	0.0003	2460
Input 81	1747	90	713	0.5	1	0.00015	1640
Input 82	1718	87	678	0.5	1	0.00015	1640
Input 83	1736	107	692	0.5	1	0.00015	1640
Input 84	1785	82	726	0.5	1	0.00015	1640
Input 85	1789	88	720	0.5	1	0.00015	1640

Table A.1: *Impact of materials supply parameters - Input (continued)*

	number of parts	number of stations	number of families	Δ^k	B^k	τ^{bulk}/τ^k	D^k
Input 86	1776	95	695	1.5	1	0.00015	1640
Input 87	1823	106	715	1.5	1	0.00015	1640
Input 88	1798	92	720	1.5	1	0.00015	1640
Input 89	1748	96	699	1.5	1	0.00015	1640
Input 90	1765	97	688	1.5	1	0.00015	1640
Input 91	1748	100	671	0.5	5	0.00015	1640
Input 92	1719	93	630	0.5	5	0.00015	1640
Input 93	1761	96	682	0.5	5	0.00015	1640
Input 94	1771	88	680	0.5	5	0.00015	1640
Input 95	1859	81	705	0.5	5	0.00015	1640
Input 96	1820	96	748	1.5	5	0.00015	1640
Input 97	1756	92	706	1.5	5	0.00015	1640
Input 98	1850	105	735	1.5	5	0.00015	1640
Input 99	1715	80	683	1.5	5	0.00015	1640
Input 100	1819	93	707	1.5	5	0.00015	1640
Input 101	1819	100	752	0.5	1	0.0003	1640
Input 102	1770	96	738	0.5	1	0.0003	1640
Input 103	1724	93	693	0.5	1	0.0003	1640
Input 104	1767	98	660	0.5	1	0.0003	1640
Input 105	1703	95	668	0.5	1	0.0003	1640
Input 106	1798	94	723	1.5	1	0.0003	1640
Input 107	1798	101	735	1.5	1	0.0003	1640
Input 108	1832	93	652	1.5	1	0.0003	1640
Input 109	1819	81	711	1.5	1	0.0003	1640
Input 110	1753	81	709	1.5	1	0.0003	1640
Input 111	1744	96	730	0.5	5	0.0003	1640
Input 112	1752	94	721	0.5	5	0.0003	1640
Input 113	1786	98	712	0.5	5	0.0003	1640
Input 114	1798	85	704	0.5	5	0.0003	1640
Input 115	1826	94	697	0.5	5	0.0003	1640
Input 116	1771	96	672	1.5	5	0.0003	1640
Input 117	1767	97	681	1.5	5	0.0003	1640
Input 118	1769	91	723	1.5	5	0.0003	1640
Input 119	1791	94	710	1.5	5	0.0003	1640
Input 120	1784	86	689	1.5	5	0.0003	2460
Input 121	1790	103	718	0.5	1	0.00015	2460
Input 122	1764	104	711	0.5	1	0.00015	2460
Input 123	1811	109	780	0.5	1	0.00015	2460
Input 124	1802	94	728	0.5	1	0.00015	2460
Input 125	1765	86	718	0.5	1	0.00015	2460
Input 126	1746	96	720	1.5	1	0.00015	2460
Input 127	1769	94	699	1.5	1	0.00015	2460
Input 128	1708	89	701	1.5	1	0.00015	2460
Input 129	1805	98	707	1.5	1	0.00015	2460
Input 130	1752	97	704	1.5	1	0.00015	2460
Input 131	1750	86	736	0.5	5	0.00015	2460
Input 132	1737	91	682	0.5	5	0.00015	2460
Input 133	1752	92	686	0.5	5	0.00015	2460
Input 134	1753	96	742	0.5	5	0.00015	2460
Input 135	1866	93	735	0.5	5	0.00015	2460
Input 136	1787	95	717	1.5	5	0.00015	2460
Input 137	1816	86	749	1.5	5	0.00015	2460
Input 138	1774	89	731	1.5	5	0.00015	2460
Input 139	1792	104	717	1.5	5	0.00015	2460
Input 140	1791	88	659	1.5	5	0.00015	2460
Input 141	1837	92	674	0.5	1	0.0003	2460
Input 142	1764	94	695	0.5	1	0.0003	2460
Input 143	1764	88	714	0.5	1	0.0003	2460
Input 144	1788	85	734	0.5	1	0.0003	2460
Input 145	1783	90	671	0.5	1	0.0003	2460

Table A.1: *Impact of materials supply parameters - Input (continued)*

	number of parts	number of stations	number of families	Δ^k	B^k	τ^{bulk}/τ^k	D^k
Input 146	1801	91	702	1.5	1	0.0003	2460
Input 147	1745	92	677	1.5	1	0.0003	2460
Input 148	1812	96	742	1.5	1	0.0003	2460
Input 149	1822	103	739	1.5	1	0.0003	2460
Input 150	1798	87	651	1.5	1	0.0003	2460
Input 151	1817	98	702	0.5	5	0.0003	2460
Input 152	1723	89	707	0.5	5	0.0003	2460
Input 153	1788	103	710	0.5	5	0.0003	2460
Input 154	1722	87	660	0.5	5	0.0003	2460
Input 155	1817	89	720	0.5	5	0.0003	2460
Input 156	1734	94	663	1.5	5	0.0003	2460
Input 157	1812	86	780	1.5	5	0.0003	2460
Input 158	1801	93	682	1.5	5	0.0003	2460
Input 159	1757	90	685	1.5	5	0.0003	2460
Input 160	1756	98	687	1.5	5	0.0003	2460

Table A.2: *Impact of materials supply parameters - Results*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
With space constraint													
Input 1	3.95	394236	85342	25569	50987	48366	77767	85897	4621	15685	60.1%	61	49.5%
Input 2	3.22	341089	68059	18339	39583	73788	65019	61843	4325	10134	58.3%	51	44.1%
Input 3	3.62	321392	63205	22276	43290	41061	66294	68868	4600	11797	56.3%	52	44.3%
Input 4	2.72	338497	70123	19795	46554	41056	75218	68369	5834	11549	58.7%	59	42.9%
Input 5	3.55	340449	68847	19190	42397	56722	71393	66190	4342	11368	60.0%	56	43.0%
Input 6	4.15	368319	90524	55379	35313	42821	70118	58782	5190	10194	55.7%	55	49.4%
Input 7	3.08	424333	95911	53506	46284	58049	90516	62277	7698	10092	63.8%	71	52.9%
Input 8	4.39	395435	102790	49591	45582	51702	75218	55205	6128	9220	56.8%	59	48.4%
Input 9	3.80	370523	102310	46782	34343	51442	68843	52419	5013	9371	54.7%	54	40.0%
Input 10	4.33	402295	87141	57584	46477	45603	86692	62736	7100	8965	60.1%	68	53.8%
Input 11	3.11	327629	53746	22813	46357	35052	81592	70311	6503	11256	71.4%	64	53.3%
Input 12	4.47	348775	81449	20110	38017	58765	72668	60341	5128	12295	57.09%	57	47.9%
Input 13	3.70	346433	65205	24245	37993	41765	85417	72322	6750	12735	65.46%	67	53.5%
Input 14	3.30	357584	61068	21672	42658	42925	89241	76984	6629	16408	64.0%	70	47.0%
Input 15	2.94	421770	59294	23972	48443	68834	109639	86341	10395	14852	69.4%	86	61.3%
Input 16	3.97	408196	112250	46318	41870	58173	80317	52689	7233	9345	59.2%	63	52.3%
Input 17	3.20	395327	94361	49158	47014	54972	79042	56087	6693	8000	55.8%	62	41.1%
Input 18	3.83	384519	90616	51651	42053	50468	76493	57357	6310	9570	61.1%	60	47.3%
Input 19	3.92	348495	80051	44192	49891	45776	66294	49936	5232	7124	55.2%	52	41.2%
Input 20	3.17	356564	91329	40884	39016	48662	70118	51785	5507	9263	56.5%	55	47.8%
Input 21	3.27	342469	44151	24258	29835	24458	101990	95594	8755	13428	73.1%	80	59.0%
Input 22	4.13	360397	67680	22052	47714	36847	84142	82365	6168	13430	62.1%	66	47.6%
Input 23	2.66	331802	59833	19759	33026	40046	82867	77582	5940	12749	62.7%	65	48.9%
Input 24	2.83	333150	71097	17453	36965	43991	77767	69053	6045	10779	60.8%	61	45.3%
Input 25	2.61	370055	73525	22076	50728	42992	75218	85516	4894	15106	61.9%	59	51.1%
Input 26	4.45	434992	107730	58034	39344	54819	85417	71647	8568	9433	60.7%	67	51.1%
Input 27	4.52	463284	131552	39900	38151	113363	70118	55257	5877	9066	57.4%	55	47.1%
Input 28	5.73	422358	96455	54644	43799	57139	81592	70262	7056	11412	57.2%	64	51.2%
Input 29	6.36	368425	77131	52850	42442	47372	71393	62756	4981	9500	57.5%	56	47.3%
Input 30	3.86	413572	123183	41147	39780	74062	68843	53434	5669	7454	51.4%	54	46.9%
Input 31	4.41	368022	78253	22038	37143	46836	84142	79771	6685	13155	60.9%	66	52.2%
Input 32	3.59	353008	64114	20962	43951	40475	86692	77373	7519	11923	60.0%	68	50.5%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 33	2.39	352172	72970	19670	49776	37223	81592	71376	6742	12825	62.2%	64	56.6%
Input 34	3.87	371847	56673	27799	41108	35066	90516	98554	6232	15899	63.4%	71	54.3%
Input 35	2.69	333766	61557	18703	36511	50132	77767	70435	5971	12689	61.1%	61	47.8%
Input 36	3.73	393887	110048	45032	45633	49929	71393	57641	5669	8543	57.5%	56	45.1%
Input 37	3.53	387700	93047	54788	44495	49341	71393	60167	5958	8511	53.9%	56	36.0%
Input 38	3.47	343662	87064	46183	34220	46934	62469	53568	5016	8209	56.4%	49	43.3%
Input 39	4.44	419484	118154	47994	37527	67736	73943	58649	5580	9901	56.7%	58	47.3%
Input 40	3.73	378190	103885	43781	42497	61052	65019	49637	5361	6959	55.9%	51	46.8%
Input 41	3.03	380207	83799	18470	41836	56036	103265	61714	5627	9460	55.8%	54	44.2%
Input 42	2.73	399909	97307	19179	46319	61041	97528	63427	4501	10608	62.9%	51	50.0%
Input 43	4.09	382176	76118	22836	39235	46008	109002	72156	5468	11353	58.5%	57	48.4%
Input 44	3.55	376739	64763	18620	35581	48143	126213	66386	8172	8863	59.8%	66	46.7%
Input 45	3.25	451661	76125	22757	42284	92372	126213	73119	7968	10823	60.4%	66	48.4%
Input 46	3.78	426978	106433	43343	45917	62749	103265	51461	5189	8623	55.9%	54	45.5%
Input 47	3.95	422926	107844	36868	43925	70221	103265	47721	6243	6840	55.1%	54	53.5%
Input 48	4.22	444372	95170	50728	47384	72861	110914	52513	6607	8194	53.5%	58	41.0%
Input 49	4.20	417164	116089	39638	38109	63415	99440	48244	6222	6007	47.5%	52	42.9%
Input 50	6.00	376019	91375	42214	32046	44155	101353	50525	5411	8941	54.4%	53	46.1%
Input 51	3.01	344496	74314	15910	41739	49193	97528	52130	5501	8181	56.1%	51	45.2%
Input 52	3.66	375240	76466	20746	35450	48617	110914	66548	5776	10723	63.5%	58	52.9%
Input 53	2.70	396695	78311	22740	49289	41375	118563	68232	6111	12074	63.3%	62	58.0%
Input 54	3.20	407792	75901	19498	43786	62676	124300	63969	6756	10906	60.5%	65	51.6%
Input 55	4.33	373765	72337	17009	49362	48901	110914	58263	6267	10713	58.5%	58	46.0%
Input 56	5.13	407581	105870	48191	41312	55241	93703	50440	4992	7832	54.6%	49	45.7%
Input 57	4.09	404943	90589	44743	44251	51547	107090	51650	6446	8627	57.0%	56	52.8%
Input 58	5.72	409955	101704	46918	37575	57007	103265	49114	5697	8675	59.3%	54	51.7%
Input 59	4.01	403071	90090	48160	47412	55053	101353	48496	5675	6834	54.8%	53	48.4%
Input 60	2.64	383661	92652	40771	39807	59046	91791	46511	4442	8642	60.4%	48	44.7%
Input 61	2.78	441924	86817	22142	45418	64536	124300	81074	7106	10531	62.6%	65	46.2%
Input 62	3.02	369830	70893	19304	48902	33157	110914	70925	6070	9665	61.4%	58	50.5%
Input 63	3.13	430746	88973	18690	41719	79909	110914	73483	5492	11566	55.6%	58	43.1%
Input 64	4.16	380959	75700	20221	34000	65356	97528	73131	4284	10738	62.8%	51	48.4%
Input 65	3.22	462018	90979	19135	36449	71978	143424	80385	7304	12364	57.9%	75	47.3%
Input 66	3.84	389122	92494	46008	34093	53644	95616	53701	5573	7994	57.9%	50	47.3%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 67	4.81	427378	105980	42726	39802	62672	105177	56462	5943	8615	53.6%	55	45.4%
Input 68	5.87	437009	112020	46231	36166	49022	118563	59305	6714	8988	56.0%	62	48.9%
Input 69	4.49	440316	118481	40766	41430	57796	109002	57705	6767	8370	56.9%	57	44.1%
Input 70	3.30	453973	124738	43829	43031	69983	103265	54760	6053	8314	56.0%	54	41.7%
Input 71	4.00	394804	79230	21720	46838	49203	109002	72219	5964	10628	54.7%	57	41.1%
Input 72	3.11	382590	86875	17768	38822	58927	101353	63945	5051	9850	58.4%	53	47.3%
Input 73	3.60	398441	81294	23256	52706	31458	112826	80253	5827	10822	64.5%	59	48.8%
Input 74	3.17	370576	78960	19689	34560	45242	109002	68168	6661	8294	57.7%	57	42.7%
Input 75	2.82	342819	71106	17089	36998	37786	101353	63740	5961	8787	60.6%	53	49.5%
Input 76	3.20	426912	107727	47784	35905	68017	99440	55750	6260	6029	56.2%	52	43.5%
Input 77	3.87	391690	97682	44485	33615	46028	103265	53125	5189	8302	53.7%	54	45.1%
Input 78	5.11	416379	121016	42879	40950	56417	91791	50415	5174	7737	53.6%	48	39.4%
Input 79	3.52	408120	104395	45124	42842	51072	97528	54139	5087	7935	52.7%	51	41.2%
Input 80	4.09	410737	118673	43995	37469	74156	78405	47221	4422	6396	53.3%	41	41.5%
Input 81	3.81	344984	61965	21615	46404	32390	85417	76851	6078	14264	63.9%	67	52.2%
Input 82	2.89	313590	52902	22558	43134	31295	71393	75249	4429	12631	62.0%	56	51.7%
Input 83	3.82	365337	66677	22477	54800	51526	76493	74444	4703	14218	58.5%	60	44.9%
Input 84	3.06	385202	64419	24884	41140	45229	98165	87717	7669	15979	62.4%	77	54.9%
Input 85	4.04	356810	73417	19899	52522	48519	77767	67162	6163	11361	60.7%	61	51.1%
Input 86	4.55	380534	110949	44139	40210	55632	63744	52011	4535	9314	55.1%	50	45.3%
Input 87	3.97	379442	95644	44481	43837	58644	70118	51220	6046	9451	56.7%	55	41.5%
Input 88	7.16	379533	87948	45185	45901	72374	63744	50955	4698	8729	54.2%	50	42.4%
Input 89	5.39	383140	92257	40898	41828	68470	73943	50805	6907	8034	53.6%	58	46.9%
Input 90	4.13	342917	96854	36439	38832	53179	63744	42707	5221	5940	54.4%	50	43.3%
Input 91	2.78	366144	72250	20761	36933	66051	80317	73074	5947	10811	57.4%	63	42.0%
Input 92	4.05	331692	60747	18937	30175	38170	94341	68500	7060	13763	60.6%	74	47.3%
Input 93	4.19	325550	66934	18289	49540	36050	73943	63545	5667	11582	59.2%	58	45.8%
Input 94	3.53	329934	67316	19536	41137	37241	79042	67717	5594	12351	65.3%	62	54.5%
Input 95	3.05	308238	53442	22511	33007	32594	77767	70817	5381	12718	66.9%	61	54.3%
Input 96	3.33	414383	88328	54635	54809	61976	81592	56490	6931	9624	60.3%	64	47.9%
Input 97	3.39	384462	99283	48602	40003	57136	73943	51039	6313	8144	58.9%	58	47.8%
Input 98	3.91	353963	102769	33005	51923	60330	54820	39788	4085	7243	45.7%	43	36.2%
Input 99	5.25	343707	76969	47036	33053	53133	66294	52524	5172	9527	63.3%	52	52.5%
Input 100	5.72	387470	91911	44993	45325	45652	84142	56456	7551	11442	56.1%	66	45.2%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 101	3.83	382986	76673	23129	46498	37800	86692	90427	6030	15739	61.5%	68	48.0%
Input 102	4.89	356259	67782	23778	48375	30855	82867	84314	5803	12484	62.6%	65	52.1%
Input 103	4.50	321221	60567	20831	39320	36213	76493	71149	5795	10854	64.2%	60	51.6%
Input 104	2.89	343126	66775	19861	46087	45746	70118	77441	4708	12390	59.3%	55	49.0%
Input 105	3.03	342822	56129	19358	41320	56068	76493	76351	5107	11996	62.8%	60	46.3%
Input 106	3.11	438891	134751	50168	31874	88669	62469	57510	4935	8515	55.2%	49	44.7%
Input 107	5.01	382509	97217	47176	47716	40513	75218	60024	6150	8497	54.4%	59	40.6%
Input 108	3.67	401678	111393	40377	32423	84401	67568	51757	5866	7893	52.9%	53	46.2%
Input 109	5.05	385254	89961	46546	42352	48219	81592	60054	7899	8631	59.5%	64	55.6%
Input 110	6.22	393266	108414	48007	37911	53025	71393	59009	5577	9929	57.8%	56	55.6%
Input 111	3.61	375619	76490	21497	46736	50467	82867	79122	6200	12241	60.7%	65	46.9%
Input 112	2.97	373268	82650	20430	32617	55154	84142	78749	7892	11635	56.7%	66	41.5%
Input 113	4.00	349979	74867	21302	36897	47988	76493	74839	5038	12557	60.6%	60	48.0%
Input 114	4.17	340203	60101	22011	41027	39586	80317	79566	5157	12438	68.3%	63	63.5%
Input 115	2.58	354906	70171	21935	38463	40439	84142	81179	6255	12321	62.7%	66	47.9%
Input 116	3.66	383919	101335	40084	37950	71370	70118	49928	6853	6281	48.3%	55	45.8%
Input 117	4.53	352652	91239	44866	43163	47222	61194	52824	3976	8170	54.0%	48	44.3%
Input 118	3.64	440263	113902	42184	52921	71642	84142	58323	9290	7860	60.4%	66	47.3%
Input 119	6.14	448196	133819	44765	42130	82837	72668	57211	7211	7554	56.0%	57	44.7%
Input 120	3.27	408264	93974	50081	33880	51236	91791	66785	8625	11893	58.2%	72	52.3%
Input 121	3.87	369968	75204	18696	45295	43598	107090	63923	6053	10109	56.3%	56	37.9%
Input 122	4.44	393258	82174	20293	46744	56038	105177	66591	4871	11369	56.2%	55	43.3%
Input 123	5.38	425523	105724	18626	52017	64359	107090	62523	5111	10073	49.6%	56	40.4%
Input 124	3.30	396605	82192	19142	52676	56720	109002	61942	6218	8712	52.8%	57	42.6%
Input 125	3.50	356224	77167	16078	45490	61753	87966	53506	4359	9905	53.6%	46	43.0%
Input 126	3.50	402285	104714	36282	41777	65759	95616	45048	5865	7225	52.6%	50	41.7%
Input 127	3.50	408313	93726	39778	47295	61018	103265	50266	5584	7382	53.5%	54	44.7%
Input 128	3.86	381979	87873	43225	34098	56946	99440	47628	6461	6309	49.9%	52	41.6%
Input 129	4.89	432342	101769	35223	40545	75646	112826	51486	6393	8454	57.2%	59	48.0%
Input 130	4.81	404747	105156	38071	42075	63566	95616	47219	5273	7771	58.8%	50	46.4%
Input 131	6.85	397819	82612	21718	46582	59402	107090	64506	5936	9973	60.1%	56	47.7%
Input 132	3.97	352062	72811	16043	56072	35941	101353	55019	5659	9164	62.3%	53	51.6%
Input 133	3.17	338107	60762	20682	36848	45552	97528	61406	5329	10000	58.3%	51	43.5%
Input 134	4.01	364200	62211	23151	36560	39831	112826	71785	6110	11726	57.6%	59	43.8%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 135	3.50	422524	67742	21913	44380	66052	128125	75606	7113	11594	61.5%	67	52.7%
Input 136	3.37	513654	130949	42333	35262	132376	109002	50320	6548	6865	52.7%	57	44.2%
Input 137	5.37	424599	99302	41335	50145	54873	114739	50317	7396	6493	59.0%	60	50.0%
Input 138	3.50	434777	83857	46756	39558	49356	139599	58515	8324	8812	56.8%	73	46.1%
Input 139	3.86	413881	101303	39152	43923	65958	105177	45885	5797	6686	54.0%	55	42.3%
Input 140	3.95	372775	89222	39148	32882	54540	99440	44723	5552	7269	56.7%	52	44.3%
Input 141	3.72	443109	94277	20035	35716	90304	110914	75327	5746	10790	63.6%	58	48.9%
Input 142	4.48	379605	83725	17109	36720	56093	105177	65802	5887	9091	61.2%	55	53.2%
Input 143	5.64	421323	99179	20523	35784	58695	112826	77505	6644	10168	56.9%	59	45.5%
Input 144	4.11	445637	103248	22193	38453	67376	118563	78693	6468	10642	61.2%	62	55.3%
Input 145	3.23	388444	86109	21882	27510	68366	101353	69402	5274	8549	57.3%	53	45.6%
Input 146	7.11	417436	117633	42608	34678	57914	93703	57322	4872	8706	52.9%	49	42.9%
Input 147	5.12	380922	99829	35188	35799	58978	89879	49455	5710	6085	51.1%	47	39.1%
Input 148	3.95	447582	116911	45321	64085	60600	91791	54591	4631	9653	53.8%	48	39.6%
Input 149	4.75	434789	111857	39773	40367	70264	105177	53920	6238	7193	51.8%	55	41.7%
Input 150	2.81	389934	91197	38649	42459	53359	101353	49220	6024	7674	55.1%	53	48.3%
Input 151	3.99	373881	89366	17372	32180	57453	97528	65166	4790	10027	52.7%	51	39.8%
Input 152	4.16	393394	99937	21267	32378	57218	99440	69343	5639	8173	55.4%	52	46.1%
Input 153	3.76	412893	87453	20074	42202	56473	118563	70797	6544	10787	58.9%	62	44.7%
Input 154	3.30	369385	70056	17725	35369	40364	118563	70232	6721	10356	60.1%	62	50.6%
Input 155	3.73	390185	71334	21331	34515	44987	126213	74214	7192	10398	68.4%	66	57.3%
Input 156	3.14	381718	95018	45185	40776	53461	86054	49500	4569	7156	50.5%	45	41.5%
Input 157	4.56	442894	107473	56219	46206	50483	101353	66324	5464	9373	59.8%	53	51.2%
Input 158	3.53	449876	122498	41252	31834	79155	107090	54433	5889	7725	53.5%	56	39.8%
Input 159	3.45	393396	103970	39642	31449	45244	110914	48832	7534	5811	53.5%	58	46.7%
Input 160	3.22	399839	120249	41786	28496	62625	87966	47028	5697	5991	48.7%	46	36.7%
Without space constraint													
Input 1	4.03	383531	79743	28028	58441	40038	65019	91995	2133	18135	53.0%	51	44.2%
Input 2	4.59	331888	72846	18484	45596	68971	52270	59621	2549	11551	51.7%	41	37.3%
Input 3	4.32	312787	68958	22175	47627	39701	53545	65557	3026	12197	50.4%	42	40.2%
Input 4	3.03	322744	84679	18560	55810	39776	50995	58574	2424	11926	45.8%	40	33.7%
Input 5	3.92	327714	80262	18200	48728	57859	50995	58247	2390	11033	51.1%	40	37.0%
Input 6	5.45	350023	98304	54793	42307	39066	48445	53469	2342	11298	47.3%	38	39.1%
Input 7	5.37	392649	109434	52903	61000	57225	48445	50554	2753	10334	48.7%	38	36.5%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 8	3.80	375842	121857	45666	53868	52715	45896	44160	2758	8922	44.9%	36	37.4%
Input 9	4.36	350413	107185	49678	44038	48289	39521	49817	1587	10299	39.5%	31	27.8%
Input 10	4.70	370535	101960	55173	57341	43894	48445	51434	2820	9467	46.4%	38	37.6%
Input 11	3.26	309430	65635	22059	54946	35910	54820	62033	3025	11003	61.1%	43	45.7%
Input 12	4.42	333535	96158	19135	46127	60537	45896	51571	2337	11774	42.3%	36	35.1%
Input 13	4.15	328292	69011	24967	47151	33118	65019	70891	2858	15279	57.5%	51	51.2%
Input 14	3.83	340924	74278	20621	52537	43531	62469	67643	3616	16230	50.8%	49	38.0%
Input 15	3.36	396731	77880	23064	70140	67870	66294	73016	3332	15136	55.2%	52	48.4%
Input 16	4.78	389056	133704	42639	52787	59728	45896	42332	3084	8888	42.9%	36	37.5%
Input 17	5.22	368495	112561	46274	58281	56267	42071	42961	2462	7619	43.1%	33	32.6%
Input 18	5.11	361593	110657	48186	50916	51458	42071	46861	2164	9279	45.7%	33	33.3%
Input 19	3.45	331577	103997	38618	58892	49994	34422	37545	2227	5883	36.3%	27	25.8%
Input 20	3.98	345156	105399	39169	48535	47748	47170	45191	2412	9532	44.7%	37	38.9%
Input 21	4.22	307027	58670	23402	46666	18498	59919	82629	2063	15181	64.1%	47	53.8%
Input 22	3.86	345643	86348	20646	59677	38530	54820	70231	2456	12935	47.8%	43	37.9%
Input 23	3.31	310774	72475	18880	42427	35909	56095	68608	2415	13966	51.9%	44	38.3%
Input 24	4.38	315873	83902	16695	46470	44505	50995	59936	2742	10627	49.2%	40	37.9%
Input 25	2.72	363400	90628	20742	57646	45032	56095	76277	2476	14505	50.9%	44	42.6%
Input 26	5.86	411211	114502	59920	53327	51816	50995	66868	3466	10316	49.1%	40	39.4%
Input 27	6.15	448909	141506	38986	44415	109120	50995	50259	3314	10314	46.3%	40	39.1%
Input 28	6.22	398871	111889	53288	55860	55665	47170	60934	2220	11846	45.3%	37	40.7%
Input 29	4.72	344388	95362	48300	49803	48940	40796	50063	2085	9039	46.5%	32	33.0%
Input 30	3.80	396151	139937	38881	50335	63947	44621	45651	2352	10429	34.2%	35	29.2%
Input 31	4.09	347498	84344	22836	48557	44031	54820	76820	2111	13980	49.6%	43	41.1%
Input 32	4.20	327955	77780	20602	55719	39924	52270	66719	2857	12085	47.1%	41	39.4%
Input 33	3.61	334986	94043	18304	60666	40549	48445	58801	2332	11846	46.5%	38	42.2%
Input 34	3.68	350647	70134	26769	51817	35880	59919	87630	2839	15660	53.0%	47	44.6%
Input 35	3.44	316795	76175	17607	49233	51646	48445	59559	1886	12244	48.3%	38	37.0%
Input 36	3.94	375820	118206	45841	55509	41223	47170	54170	2597	11104	41.8%	37	34.1%
Input 37	4.17	369406	106479	53309	53982	44223	45896	52865	2635	10017	44.3%	36	27.9%
Input 38	5.20	328727	102951	42438	41648	47939	39521	44009	2309	7913	45.8%	31	30.9%
Input 39	4.31	397581	121619	50523	48734	59968	45896	56744	1912	12186	41.2%	36	33.0%
Input 40	5.14	364454	116155	41847	47361	62131	44621	42586	3112	6641	44.3%	35	34.0%
Input 41	3.48	355516	113863	15403	49743	64209	57369	45338	2534	7057	34.5%	30	27.9%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 42	3.48	377761	114499	18680	54298	59545	61194	56895	1603	11048	43.8%	32	33.7%
Input 43	4.05	352495	94631	21874	48772	44513	66931	62048	1933	11793	46.2%	35	36.6%
Input 44	4.09	334382	101191	15871	50933	48657	59282	47527	2211	8711	43.0%	31	31.5%
Input 45	4.04	414287	104331	21187	57438	92926	66931	58716	2098	10660	44.5%	35	34.7%
Input 46	5.26	393056	150252	29243	55310	73375	47808	29880	1692	5497	34.2%	25	24.8%
Input 47	4.12	389293	137436	30590	55069	76210	49720	32852	2337	5079	33.8%	26	25.7%
Input 48	4.65	400127	128899	43746	59243	78967	45896	34795	2185	6398	31.8%	24	22.9%
Input 49	4.89	376767	143424	35998	49635	66128	40159	34590	1625	5209	28.7%	21	23.1%
Input 50	4.45	340677	121169	36514	42833	51908	43983	35975	1634	6661	32.9%	23	24.7%
Input 51	3.00	315700	94157	15275	51774	46451	53545	44077	1434	8988	40.8%	28	29.0%
Input 52	5.03	344372	96644	19702	44448	51274	65019	55221	2123	9941	47.4%	34	40.0%
Input 53	3.80	362418	100104	21000	58188	47209	68843	54649	2066	10358	46.1%	36	40.7%
Input 54	3.50	366485	88732	20042	60371	55314	68843	58679	1432	13072	41.8%	36	35.2%
Input 55	3.23	342393	107162	13519	60163	59262	53545	38936	2141	7665	35.4%	28	27.0%
Input 56	4.33	378750	122526	46861	48874	53869	53545	43006	1833	8236	38.5%	28	29.3%
Input 57	4.45	376037	121298	37765	53172	56897	59282	37512	3058	7054	41.6%	31	32.6%
Input 58	4.73	378904	131033	40596	44170	63634	53545	36739	2463	6726	40.2%	28	31.0%
Input 59	3.16	372178	126917	39703	58542	57669	47808	33403	2073	6064	33.0%	25	26.4%
Input 60	6.50	363262	114078	34921	44586	62996	59282	37193	2727	7480	49.2%	31	34.1%
Input 61	4.62	402337	102452	21897	57113	64856	70756	72282	2544	10437	47.1%	37	35.5%
Input 62	4.94	332015	95120	17586	60903	33141	57369	56552	1674	9669	41.6%	30	31.2%
Input 63	4.50	398109	105164	17919	49231	78536	68843	64252	2194	11970	42.1%	36	32.4%
Input 64	3.45	357461	102063	18273	41631	70770	53545	60182	1853	9146	40.9%	28	28.0%
Input 65	3.69	403810	127560	16449	54870	77680	57369	57908	1287	10687	29.1%	30	25.3%
Input 66	3.85	366664	127605	37481	41544	59827	53545	37986	2501	6175	39.9%	28	30.8%
Input 67	4.04	386891	158516	29216	54625	73972	34422	29514	1336	5291	24.7%	18	18.6%
Input 68	5.18	392084	142805	41086	45723	53869	55457	43508	2075	7562	37.1%	29	31.5%
Input 69	5.21	402992	151609	33740	51276	62018	53545	40949	2728	7128	38.0%	28	26.5%
Input 70	4.79	419414	143730	41226	54770	71912	53545	44255	2230	7747	40.2%	28	28.1%
Input 71	4.58	363717	102770	19852	56997	51012	63106	58314	1569	10095	40.2%	33	29.9%
Input 72	4.33	355754	106290	16408	47116	59122	61194	54002	1831	9793	45.0%	32	34.4%
Input 73	7.25	363343	99335	21912	60894	32964	66931	68437	2491	10379	51.6%	35	36.9%
Input 74	3.43	340380	106679	17821	49881	47662	55457	53337	1961	7582	39.2%	29	28.1%
Input 75	4.33	318047	90266	15935	45015	38611	63106	53784	2785	8544	47.7%	33	35.5%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 76	5.52	394259	135622	42831	46649	69455	47808	44156	2132	5606	37.0%	25	28.2%
Input 77	3.77	355000	148247	30428	44747	54804	40159	29641	1255	5720	29.3%	21	20.9%
Input 78	4.60	390379	165435	33692	51684	61733	38246	32341	1073	6174	28.2%	20	20.2%
Input 79	4.00	377969	134726	39139	52224	57102	47808	38917	1893	6161	32.7%	25	23.5%
Input 80	3.30	391427	145768	37223	42328	81233	43983	34115	2462	4314	36.8%	23	28.0%
Input 81	3.83	322996	82700	20202	56861	36135	48445	63848	1644	13163	48.7%	38	37.8%
Input 82	4.07	301439	65986	21545	48939	31894	50995	67259	2367	12455	49.1%	40	40.2%
Input 83	3.46	349772	82560	21047	61618	53835	50995	64104	2076	13539	44.8%	40	31.8%
Input 84	3.96	358042	78512	24210	54924	36832	65019	77872	2225	18449	52.9%	51	47.6%
Input 85	4.39	337507	73012	21868	61828	35998	57369	69466	2922	15044	50.5%	45	44.3%
Input 86	4.21	366167	120074	45609	45546	56038	40796	46842	2067	9195	42.9%	32	31.6%
Input 87	5.96	364218	119217	38168	50759	64884	42071	38573	2932	7615	42.5%	33	29.2%
Input 88	5.08	366395	109153	39493	53664	74904	39521	39446	2230	7985	39.4%	31	29.3%
Input 89	4.89	364776	110150	38351	50769	69291	44621	40232	3570	7793	40.4%	35	34.4%
Input 90	4.22	325059	111249	33062	45648	55068	38246	33534	2866	5384	41.4%	30	29.9%
Input 91	3.69	345024	90698	19109	44437	66571	49720	60816	3014	10658	46.4%	39	31.0%
Input 92	3.33	302770	76644	18069	46398	37105	52270	56425	1783	14076	43.5%	41	35.5%
Input 93	3.22	313162	84798	16893	60566	36390	47170	53618	2244	11482	44.6%	37	33.3%
Input 94	4.12	312121	80324	18652	51129	37384	50995	59303	2026	12309	51.9%	40	42.0%
Input 95	4.17	292240	62898	22387	41265	29198	54820	65811	2145	13717	55.5%	43	46.9%
Input 96	5.28	394552	102358	51656	65437	63670	52270	46327	3709	9125	50.2%	41	39.6%
Input 97	4.66	367804	116325	45999	49946	58458	44621	41481	3221	7755	44.8%	35	33.7%
Input 98	5.19	342410	116489	29711	56637	63127	35697	31978	2352	6420	35.7%	28	26.7%
Input 99	4.95	328307	88987	45728	40779	51646	43346	46011	1846	9965	51.2%	34	38.8%
Input 100	4.67	363099	106850	44533	61277	43699	45896	47077	1752	12016	42.0%	36	33.3%
Input 101	3.66	364339	92323	22129	56776	37867	57369	80209	1948	15719	49.0%	45	39.0%
Input 102	3.77	338911	85684	22205	54861	31449	57369	72312	2721	12310	51.4%	45	42.7%
Input 103	4.06	309580	70329	20309	45402	36832	57369	64914	3754	10672	54.8%	45	46.2%
Input 104	3.59	330749	73193	19698	51050	33196	59919	74755	2857	16081	48.2%	47	37.8%
Input 105	3.69	325441	73157	17971	50659	56173	48445	64801	2270	11966	47.2%	38	34.7%
Input 106	4.97	429070	141590	50680	38381	88234	43346	55571	2625	8643	45.7%	34	34.0%
Input 107	5.81	358546	120314	43514	57682	42197	38246	46418	2174	8001	38.4%	30	26.7%
Input 108	5.09	385977	118925	39974	39872	81406	47170	47167	2688	8774	41.6%	37	35.5%
Input 109	5.61	362011	103107	44971	52018	46496	50995	51395	3893	9138	49.8%	40	46.9%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 110	4.77	380300	125880	44879	44042	55131	47170	50595	3293	9310	42.1%	37	39.5%
Input 111	3.12	356253	86183	21315	57613	47264	56095	72004	2597	13183	54.0%	44	40.6%
Input 112	3.94	349192	102020	19243	45996	54726	47170	65676	2601	11761	46.6%	37	35.1%
Input 113	3.19	333580	85646	20745	46053	45780	52270	67838	2042	13206	48.4%	41	37.8%
Input 114	3.23	326039	75573	20857	48658	37713	57369	70557	2323	12989	55.5%	45	49.4%
Input 115	3.84	334158	80689	21774	48917	36448	56095	74502	2239	13495	51.5%	44	41.5%
Input 116	4.36	364305	122975	36019	49654	61414	43346	39158	2530	9209	30.8%	34	27.1%
Input 117	4.50	336263	111504	39406	48939	50384	35697	41376	1718	7240	39.7%	28	27.8%
Input 118	4.70	413141	118749	45924	65588	52061	57369	56239	3591	13620	48.8%	45	38.5%
Input 119	4.67	432740	156396	40281	53913	82822	43346	45259	3166	7558	41.8%	34	34.0%
Input 120	3.45	379552	106448	50107	53276	41406	52270	59217	2045	14784	44.8%	41	37.2%
Input 121	4.87	338027	104097	16209	56150	49320	53545	48264	2016	8426	39.9%	28	27.2%
Input 122	4.42	365391	111383	17322	54546	64236	57369	49609	1968	8958	39.1%	30	26.9%
Input 123	4.56	393267	133267	16078	63738	68178	55457	46171	1429	8949	32.4%	29	24.8%
Input 124	3.92	360847	103557	17687	66649	57882	55457	49190	2055	8370	38.5%	29	30.9%
Input 125	3.00	330708	89976	15530	53805	57083	55457	46401	1178	11278	42.2%	29	31.4%
Input 126	4.42	368948	132553	33145	52138	68967	40159	34110	1595	6281	31.5%	21	21.9%
Input 127	4.08	372429	139904	27156	58519	69182	42071	28628	1989	4980	32.3%	22	23.4%
Input 128	4.17	348070	120742	35359	47861	58445	45896	31912	1988	5868	31.7%	24	25.8%
Input 129	4.45	390442	142531	26548	53301	85705	43983	30983	1896	5495	32.5%	23	23.5%
Input 130	5.40	380370	120609	37988	49642	65724	55457	41410	2404	7136	39.4%	29	29.9%
Input 131	3.80	370237	89000	22248	57943	55990	70756	61185	2137	10977	47.4%	37	38.4%
Input 132	4.00	328504	97098	14099	67581	36485	59282	43029	1926	9004	44.9%	31	34.1%
Input 133	4.03	316009	82999	18372	45679	47114	61194	48849	2262	9540	47.9%	32	34.8%
Input 134	3.28	332435	83344	21706	51232	40389	63106	59474	1621	11562	42.3%	33	32.3%
Input 135	3.86	383094	95960	18808	57231	74284	68843	56098	2699	9172	45.0%	36	35.5%
Input 136	4.50	471717	147962	39874	45653	132951	55457	40682	2443	6696	37.8%	29	29.5%
Input 137	4.45	384925	127968	35503	64030	57786	55457	35873	2672	5636	43.3%	29	32.6%
Input 138	4.03	365716	131215	35967	61884	56583	40159	32028	1194	6686	29.8%	21	23.6%
Input 139	4.22	373724	137162	29606	57012	71155	43983	27915	1734	5158	30.7%	23	22.1%
Input 140	3.45	336027	130580	27493	41919	63985	40159	25614	1787	4491	32.7%	21	23.9%
Input 141	3.75	409013	118475	18111	45834	93045	61194	60425	1945	9984	46.2%	32	32.6%
Input 142	3.50	353541	102073	16015	47478	55712	65019	55722	2319	9203	47.3%	34	35.1%
Input 143	4.59	394356	114920	20065	45467	56719	72668	70809	2958	10749	42.1%	38	35.2%

Table A.2: *Impact of materials supply parameters - Results (continued)*

	CPU time	Total cost	Picking bulk	Picking kit	Trpt pallets	Trpt boxes	Trpt kits	Kitting	Repl pallets	Repl boxes	% kitting	# of kits	% of stations with kitting
Input 144	3.75	415254	124941	20584	46785	69965	74580	65399	3120	9880	44.8%	39	41.2%
Input 145	3.09	360052	104214	21286	35710	67612	59282	61457	1721	8770	42.4%	31	33.3%
Input 146	4.62	387864	129380	44017	44977	57668	49720	52084	1241	8778	37.0%	26	27.5%
Input 147	4.70	349996	119195	31491	44383	63079	45896	38309	2765	4878	37.0%	24	25.0%
Input 148	5.56	423092	145085	38942	72110	68128	49720	39536	2134	7438	37.0%	26	26.0%
Input 149	4.95	397836	146342	31544	50678	75597	49720	35839	2491	5625	35.5%	26	24.3%
Input 150	3.25	354979	143243	26784	54947	64440	34422	25311	1419	4414	25.3%	18	20.7%
Input 151	3.23	350458	100079	17064	40363	55847	65019	59532	2056	10499	43.5%	34	32.7%
Input 152	3.36	366209	108098	21198	39478	53459	66931	65187	2579	9278	45.1%	35	37.1%
Input 153	3.45	374380	104109	18894	54149	58987	66931	58653	2611	10047	44.4%	35	33.0%
Input 154	2.98	330795	102261	15679	50064	42986	55457	53231	1532	9585	38.0%	29	31.0%
Input 155	3.56	356346	95903	19779	46139	41795	76493	62140	2759	11337	52.0%	40	42.7%
Input 156	3.41	359299	120984	39414	49604	58280	45896	37421	1962	5739	35.9%	24	25.5%
Input 157	5.50	416929	141396	49214	55430	56465	53545	51389	1877	7613	39.6%	28	32.6%
Input 158	6.87	401859	160509	31098	43120	85443	40159	33886	1770	5875	30.9%	21	20.4%
Input 159	3.51	347848	147581	28381	45603	51913	42071	26335	2116	3849	31.2%	22	23.3%
Input 160	3.27	369641	149325	35079	38961	66731	40159	32688	1916	4783	32.3%	21	20.4%